MISCELLANEOUS PAPER GL-92-3

US Army Corps of Engineers

GEOTECHNICAL CENTRIFUGE USE AT UNIVERSITY OF CAMBRIDGE GEOTECHNICAL CENTRE AUGUST—SEPTEMBER 1991

by

Paul A. Gilbert

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Fery Road, Vicksburg, Mississippi 39180-6199

January 1992

Final Report

Approved For Public Release; Distribution Is Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

GEOTECHNICAL LABORATORY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1992

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Geotechnical Centrifuge Use at University of Cambridge Geotechnical Centre August - September 1991

5. FUNDING NUMBERS

6. AUTHOR(S)
Gilbert, Paul A.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station
Geotechnical Laboratory, 3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Miscellaneous Paper GL-92-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A geotechnical centrifuge applies elevated acceleration to small-scale soil models to simulate body forces and stress levels characteristic of full-size soil structures. Since the constitutive behavior of soil is stress level dependent, the centrifuge offers considerable advantage in studying soil structures using models. Geotechnical modeling as a technique for studying difficult civil engineering problems has been increasing in use worldwide since the mid-1980's. However, the technique has been used in England at the Geotechnical Centrifuge Centre of Cambridge University since the late 1960's. This team, under the leadership of Professor Andrew Schofield, is recognized as the world's best and most experienced in geotechnical centrifuge research.

The US Army Engineer Waterways Experiment Station (WES) has been doing research on geotechnical centrifuges owned by others in recent years. For this reason, it is important that WES have personnel familiar with the operation and

(Continued)

14. SUBJECT TERMS

Centrifuge modeling	Modeling
Centrifuge operation	Physical modeling
Geotechnical centrifuge	Similitude

15. NUMBER OF PAGES
83

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

13. (Concluded)

use of geotechnical centrifuges. Training under the guidance of those who have mastered the technology is the only way to obtain the required familiarity and expertise in centrifuge modeling. This report describes details of a training visit by the author at the Geotechnical Centrifuge Centre at Cambridge University. The visit was supported by US Army ACTEDS resources. The objectives of the training visit were to observe and document various aspects of centrifuge modeling including: (a) facility operation, (b) experiment design, (c) model package preparation and instrumentation, (d) model package mounting and loading, (e) data acquisition, and (f) model package assembly.

Several experiments were observed and described in relative detail, including experiments in soil dynamics and liquefaction study, an experiment investigating leaning towers on soft foundations, and an experiment investigating migration of hot pollutants through soils.

Guidance on facility operation and safety precautions was given by Professor A. N. Schofield and is described in detail in the report.

PREFACE

This report is the result of a training visit by the author to the Geotechnical Centrifuge Centre (GCC), Cambridge University Engineering Department (CUED), Cambridge, England, where the use and operation of geotechnical centrifuges was observed and studied for approximately two months during August and September 1991. The visit was sponsored, in part, by the U.S. Army ACTEDS (Army Civilian Training, Education and Development System) Program; selection of the author for this training visit was made by the Functional Chief's Representative for Career Program 18. The geotechnical centrifuge research team at Cambridge University is led by Professor Andrew N. Schofield, Professor of Civil Engineering, Head of the Soil Mechanics Group and Head of Engineering Division D: Soil Mechanics and Structures. Dr. Ryan Phillips, Senior Research Assistant and geotechnical centrifuge manager, GCC/CUED, was the point of contact for the author while at the Centre.

This report was prepared by Mr. Paul A. Gilbert, Soils Research Facility, Soils Research Center (SRC), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES) under the direct supervision of Mr. Gene P. Hale, Chief, SRC, and under the general supervision of Dr. Don C. Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Chief, GL. Critical review and comments were provided by Professor Andrew N. Schofield and Dr. Ryan Phillips. Appreciation is expressed to Mr. Christopher H. Collison, Senior Technician, GCC/CUED, and Mr. N. H. Baker, Assistant Technical Officer/CUED for their advice, assistance, and information shared during the visit.

Commander and Director of WES during the preparation and publication of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic inches	16.38706	cubic centimetres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	centimetres
horsepower (550 ft-lb (force) per second)	745.6999	watts
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	645.16	square millimetres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

GEOTECHNICAL CENTRIFUGE USE AT UNIVERSITY OF CAMBRIDGE GEOTECHNICAL CENTRE, AUGUST - SEPTEMBER 1991

PART I: INTRODUCTION

Background

1. The response of soil and earth materials to loading is complicated and highly nonlinear; additionally, stress-strain and strength characteristics of soil are stress state dependent. Geometry and boundary conditions in a soil structure of interest may be so complex that when combined with material (soil) behavior, only an approximate mathematical solution of the system load response may be possible. In such cases, there is a possibility of achieving verification of such approximate solutions to system response through physical modeling. In physical modeling, a small-scale model of a structure of interest is prepared and subjected to (scaled) loading similar to that expected in the full-size structure or prototype. Since soil is a material with stress-dependent constitutive properties, unless small-scale models experience homologous prototype stress fields (for example, the stress due to self-weight), measurements of stress, deformation, pressure, and observed failure mechanism may be quite different in a small-scale model from that observed in a full-size prototype structure. For this reason, the geotechnical centrifuge is ideal for representing behavior of soil structures. In some cases, actual prototype soil is used as model material. Elevated static acceleration produced by the centrifuge enables duplication of stress fields within the small-scale model which occur in the prototype. Therefore, centrifuge modeling offers great advantage in investigating load response in soil structures; for example, each element of the small-scale model is constrained within a geometrically scaled mass and loaded in a manner similar to that of the corresponding prototype. Consequently, each element reacts correctly with its neighbors to reflect the integrated behavior of the entire model. Therefore, a well thought-out centrifuge model experiment has an indisputable connection/association with its corresponding prototype structure and yields data that are credible and tenable and cannot be dismissed.

2. A centrifuge model will not exactly replicate every aspect of soil behavior, but by testing models of the same prototype at different scaling ratios, factors determining certain features of soil behavior can be identified. It must be realized that the insight gained through centrifuge modeling is not without cost. Generally, a geotechnical centrifuge is a large, complex piece of machinery, which represents substantial capital investment in equipment as well as personnel trained in its use and maintenance. Attention must be paid to safety at a centrifuge modeling facility because the amount of kinetic energy associated with a geotechnical centrifuge during rotation is enormous. Such energy could potentially damage components of the centrifuge or pose a significant safety problem for attending personnel if the equipment is used incorrectly, inappropriately, or without proper regard for its size and power.

3. The number of researchers using geotechnical centrifuge modeling, as well as the general acceptance of the technique, has increased substantially in the United States since the mid-1980's, although it has been used widely in research and in engineering applications in England since the late 1960's and in the Soviet Union since the early 1930's. Professor Andrew N. Schofield constructed a small geotechnical centrifuge at the University of Manchester Institute of Science & Technology in the late 1960's and was first to use a centrifuge for effective stress modeling/representation of soil structures. Shortly thereafter, Professor Schofield moved to Cambridge University, established the Geotechnical Centrifuge Centre there, and has led the Cambridge geotechnical research team since that time. The Cambridge geotechnical centrifuge team is generally acknowledged to be the state of the art in geotechnical centrifuge modeling.

4. Centrifuge modeling offers the advantages discussed above for the treatment of soil mechanics related problems, but the technique can be used very productively in other areas of civil engineering as well. Problems in structural engineering may be modeled effectively on the centrifuge because self-weight of members is an important consideration that is not easily accommodated in modeling techniques at 1-g (that is, at one earth gravity, 32.2 ft/sec^2). Soil/structure interaction is an important problem in civil engineering; this problem area and its treatment are often difficult because of the highly indeterminate nature of the systems involved. Centrifuge

modeling offers a practical and useful alternative for studying and solving these problems.

5. Problems in hydraulics and fluid mechanics may be investigated on the centrifuge since materials and parameters may be varied in models to better achieve similitude. For example, unlike fluids may be substituted in centrifuge models to achieve similitude in terms of viscous forces which would, otherwise, be difficult to achieve.

Purpose

6. Centrifuge modeling as a technique for solving certain difficult civil engineering problems is growing worldwide and gaining increasing acceptance among the geotechnical community. Geotechnical centrifuge research is performed by personnel of U.S. Army Engineer Waterways Experiment Station (WES), but the work is carried out on equipment owned by others. Research performed by WES on the geotechnical centrifuge will likely increase in quantity and complexity in the future; therefore, it is important that WES have personnel familiar with the design of centrifuge model experiments as well as the operation and use of centrifuge equipment for future work on privately owned as well as government owned centrifuges. Hands-on training under the guidance of those who have mastered this technology is the only way to gain such familiarity and expertise. Therefore, the purpose of this training visit to the Geotechnical Centrifuge Centre of Cambridge University was to observe and study various aspects of centrifuge modeling which include: (a) facility operation (including safety precautions), (b) experiment design, (c) model package preparation and instrumentation, (d) installation of model packages on the centrifuge arm, (e) centrifuge loading of model packages, (f) data acquisition, and (g) model package disassembly.

PART II: CENTRIFUGES AVAILABLE AT THE CAMBRIDGE GEOTECHNICAL CENTRIFUGE CENTRE

7. Two types of centrifuges are in use at the Cambridge Geotechnical Centrifuge Centre, the drum centrifuge and the beam centrifuge. For completeness, each will be described briefly below.

Drum Centrifuge

8. In the CUED drum centrifuge, the axis of a cylinder open on one end is aligned with the vertical direction, and the cylinder is spun to generate high centrifugal acceleration normal to the surface of the cylinder/drum. Soil specimens are formed on the inside of the cylinder as it rotates. Sand specimens are deposited while being moistened to minimize dust in the environment. After placement, specimens (while still under centrifugal acceleration) are first inundated/saturated with water from the bottom, then drained so that capillary suction will hold sand particles in place when drum rotation is stopped. A series of experiments requiring several days is generally performed on a single specimen; the centrifuge is stopped between each experiment and capillary suction prevents specimen collapse during that period. Clay specimens are placed on the drum in a state of high-water content, then centrifugal acceleration is used to normally consolidate the slurry to a desired density/effective stress. The cylinder of the Cambridge drum centrifuge is 2 m in diameter and 1 m high, and specimens are typically 150 mm deep; high acceleration (up to 500-g) can be achieved with the drum centrifuge.

9. The principal advantage of the drum centrifuge is that relatively long and homogeneous specimens are placed. Many separate loadings (from 12 to 30) may be performed on a single-drum specimen in different locations since the specimen is large in areal extent. For example, at 300-g's, the area of a drum centrifuge specimen scales to become about 1800 X 300 m. It can therefore be argued that since many loadings may be performed on "identical" specimens, the drum centrifuge is ideal for performing parametric studies. Additionally, the drum offers a very definite advantage for studying phenomena involving long models, for example, seepage/contaminant migration over long distances, stability of long slopes, etc.

10. Disadvantages of the drum are that specimen depth is somewhat limited, placement of sand specimens may be difficult, and comparably large quantities of soil are required for a specimen. For example, a 150-mm-thick specimen placed over the drum surface encompasses a total specimen volume of about 30 cu ft.

Beam Centrifuge

11. Observation and study of modeling on the large beam centrifuge at Cambridge is the primary focus of this training visit. This centrifuge consists, essentially, of a stiff compound beam section mounted on central bearings, a drive motor, and a container which holds the small-scale soil model. Soil models are prepared separately and loaded onto the centrifuge just prior to "flight." During operation, the beam is rotated in a horizontal plane about the central bearings by the drive motor to generate centrifugal acceleration. The model container/package is installed on a platform near the end of the centrifuge arm where centrifugal acceleration is greatest during rotation. In the absence of rotation, the swing hangs vertically on the centrifuge arm to align itself with the direction of gravity. The swing is mounted on hinges such that as rotational speed and therefore centrifugal acceleration increases, the package swings up to align itself with the resulting acceleration vector; consequently, this type of mounting mechanism is called the "swinging platform." (The specimen platform on the Cambridge beam centrifuge is not a true swinging platform because before acceleration level under which the experiment will be performed has been achieved, the platform is clamped, then moved to a horizontal attitude. The result is a small error in inclination between the Cambridge platform and that of a true swinging platform in which the vertical axis of the specimen is aligned with the resultant acceleration. This error in inclination (in degrees) is equal to the difference between 90 deg and the arctangent of the scaling ratio (in degrees). The only advantage of a swinging platform configuration would have been that the vertical axis of small-scale models was always aligned with the resultant of earth gravity and centrifugal acceleration, that is, "model" gravity).

12. Effective radius of the Cambridge beam centrifuge arm is 4 m, and the device is capable of accelerating a package of 900 kilograms mass to a

maximum of 155-g's. Details of the configuration and performance of the Cambridge beam centrifuge are given by Schofield (1980).

13. In addition to the large beam centrifuge, there is a smaller medical centrifuge that has a maximum model radius of 20 cm and is capable of generating a maximum acceleration of about 3,000-g. This smaller centrifuge is fitted with four true swinging buckets in which the hinge points (about which the buckets rotate) are about 11 cm from the central axis. This centrifuge is equipped with an environmental chamber in which temperature can be adjusted to levels above and below ambient; it will be used to investigate phenomena at high acceleration, although it is acknowledged that because of its small size, there will be considerable variation in acceleration over the depth of the specimen bucket. Specimen thicknesses of about 45 mm are planned; variation in <u>stress</u> over this specimen thickness can be mathematically demonstrated to be no more than ± 4.5 percent.

PART III: PROCEDURE FOR OPERATING AND COORDINATING EXPERIMENTS ON THE CAMBRIDGE BEAM CENTRIFUGE

14. The beam centrifuge at Cambridge University is a very large, complex, and powerful piece of equipment which requires the coordinated effort of a team comprised of members who have different specific knowledge, skills, and areas of responsibility. A precise procedure detailing organization of the operating team and use of the beam centrifuge has been developed and is followed strictly because it produces a safe, efficient, and successful operation. The procedure has been documented and presented by Schofield (1980) in his Rankine Lecture; it is given in Appendix 1 of that Lecture, entitled "CODE OF PRACTICE FOR SAFE OPERATION OF THE CAMBRIDGE GEOTECHNICAL BEAM CENTRIFUGE." For completeness, that appendix is included in its entirety in this report as Appendix A; however, major points will be summarized.

15. Personnel authorized to use the centrifuge are specified by the centrifuge director and include research workers, engineers, and centrifuge operators. Each of these personnel categories has very specific tasks and responsibilities in the conduct of centrifuge experiments. At least one (separate) representative from each category must be present on the team to carry out/perform the work assigned to that category. The tasks and responsibilities of each category will be briefly described below.

Research Workers

16. Research workers are generally Cambridge University engineers or visiting engineers who have sufficient knowledge of the use and purpose of centrifuge modeling to propose centrifuge research and to assume that research when the proposal is approved and the appropriate support team organized and assembled.

17. In general, research workers:

a. Plan research programs after discussions with the engineer(s) and prepare the proper approval documents.

b. Are responsible for performing calculations and providing plans and drawings to assure the engineer associated with the team that the research contemplated is completely safe before approval can be made. Additionally, research workers prepare balance calculations and obtain the engineer's signature on flight authorization documents before each flight in an authorized program.

c. Are concerned with the outcome of each experiment, are present during the mounting of each package, and have on-the-spot responsibility for all decisions made and actions taken in the research.

d. Train others in the safe operation and use of the centrifuge.

18. It is noted that when a University engineer is acting as research worker, another engineer must act as engineer in the program.

Engineers

19. Engineers are employees of Cambridge University and have sufficient knowledge and experience to:

a. Examine the experimental plans and documents of research workers.

b. Approve tests in an authorized program.

c. Serve as centrifuge operators (when not acting as engineer).

d. Serve as research workers (when not acting as engineer).

Centrifuge Operators

20. Centrifuge operators are employees of Cambridge University and have sufficient knowledge of and experience in the operation of the centrifuge to:

a. Advise and assist research workers.

b. Verify test documents.

c. Mount model packages.

d. Operate the centrifuge.

e. Execute activities directed by research workers within an approved program.

21. The operator holds the key which starts the centrifuge. Therefore, before starting, the operator has responsibility to check that all masses on the package as well as counterweights on the centrifuge arm are properly located and secure, that all obstructions and loose objects are removed from the centrifuge chamber, that all people have left the chamber, and that all lids to the chamber are secure and locked.

22. It must be noted that if, at any time, an operator is not satisfied that activities and events are normal with respect to the equipment or facility, the operator has authority to terminate that operation with or without approval of the research worker or engineer. It is the responsibility of the

centrifuge operator to ensure safety as well as preserve and protect the equipment; one important rule which guides the operator is, "No single test is more important than the equipment."

23. It is policy at the Cambridge Centrifuge Centre that the beam centrifuge be continuously manned during experiments regardless of the time duration. The attending research worker often remains at the facility during the entire experiment. Operators generally work six- to eight-hour or more shifts, depending on arrangements made and agreements among the operators prior to initiation of an experiment. A centrifuge operator must sign into the (centrifuge) log book each time the centrifuge motor is started and enter certain specific information such as the reason for starting the centrifuge and the duration of the run. During an extended experiment, a centrifuge operator does not leave his station at the Centre unless and until relieved by a replacement operator. At that time, the retiring operator signs off in the log book, and the relieving operator signs on, thus assuming responsibility for the equipment.

24. A direct statement made in Appendix A (Schofield 1980, Appendix 1) is, "Experience has shown that the presence of visitors during centrifuge flight operations is detrimental to safety and efficiency." This statement is supported enthusiastically by research teams, for a team is under a certain degree of pressure during the conduct of an experiment and should not be distracted because concentration is required and undivided attention must be given. Additionally, it is possible that unexpected events could occur during experiments that require quick and definitive action. The presence of visitors generates an air of confusion in the control room, which could lead to miscommunication among the research team or slowed reaction to an unexpected or emergency situation.

PART IV: PRACTICAL ASPECTS OF OPERATION AND USE OF A GEOTECHNICAL CENTRIFUGE

25. It must be realized that careful and extensive preparation must be made for the execution of each geotechnical centrifuge experiment. Each phenomenon investigated will likely require a unique and possibly intricate test configuration. Machine shop work will probably be required for each separate centrifuge investigation for each individual test performed. Design and manufacture of special mechanical components and transducers/sensors may be involved for some investigations, which will require coordination and interaction between, say, machinists and electronics technicians. Additionally, research schedule maintenance may depend on timely reception of items placed on order. Obviously, then efficient operation, use, and maintenance of a geotechnical centrifuge facility will involve substantial operating costs as well as require availability and cooperation of support facilities and groups such as the machine shop, the mechanical design group, instrumentation services, and procurement services.

26. Because of the probable need in centrifuge modeling for modification of many small but essential items (such as plumbing fittings and mounting hardware), one or more small metal cutting lathes along with a grinder, a small arc welding rig, and a small milling machine in the facility would be highly desirable if not absolutely essential. The principal value of such equipment onsite is that it would eliminate the necessity of and the time loss associated with having the machine shop perform such inconsequential (but necessary) work. However, it must be noted that training of personnel in the safe and efficient use of such machinery will be necessary to ensure safe operation and to realize full advantage of this auxiliary equipment.

PART V: TRANSDUCERS AND DATA ACQUISITION SYSTEM

27. Transducers/sensors to measure and allow electronic data acquisition of force, deformation, pressure, and acceleration are necessary for centrifuge modeling. It must be noted that manufacturers of electronic transducers will not, in general, warrant or recommend use of their products in the high-acceleration environment of the centrifuge. However, it has been the experience of the Cambridge research team that high-quality electronic sensors designed for use in the ambient environment (1-g) will usually withstand use in the high-acceleration environment of the beam centrifuge (provided devices selected are configured properly and aligned optimally on the centrifuge arm).

Pressure Transducers

28. Pressure transducers for instrumenting centrifuge models should be miniature, that is, no more than a half in. in size and preferably smaller. The reason for the small-size requirement is that it is often desirable to implant pressure sensors in a centrifuge model for direct internal pore pressure measurement. A transducer which is a half in. in diameter and a half in. long scales to become 50 in. in diameter and 50 in. long at 100-g. The scaled volume of the transducer increases eightfold if the acceleration doubles. It is obviously undesirable to have such a structure embedded in a small-scale model since stress fields within the body will be disrupted because of the size and stiffness of the pressure sensor (which is likely to be very different from that of the surrounding soil). If the stress fields are disturbed sufficiently, model behavior and failure mode may be affected. Additionally, electrical leads from transducers must be carried through the models to termination. The actual influence of implanted pressure transducers and their leads on model behavior has been demonstrated by the Cambridge team to influence model behavior to an extent, although this experience has not been documented in a formal publication. However, influence is minimized by using the smallest sensors available and running the leads perpendicular to the direction of acceleration (a direction in which response to the excitation does not change appreciably in a two-dimensional model).

Force Transducers

29. Force transducer configurations used in centrifuge modeling at the Geotechnical Centrifuge Centre are usually unique to a particular experiment and therefore designed and manufactured around the geometry of that experiment. Occasionally, commercially available products may be adapted; however, there are configurations with very special requirements where special transducers must be manufactured and used. Force transducers fabricated at Cambridge are normally machined from aluminum with the International Designation, 2014A-TF, and subsequently strain gauged in-house at the University work shops. This 2014A-TF aluminum is used because, in the experience of the Cambridge team, lower grades of aluminum do not machine cleanly, show a tendency for excessive strain hysteresis as the result of loading, and generally result in very unsatisfactory finished products. The cost of 2014A-TF aluminum is higher than lower grades, but higher material cost is insignificant in the overall production of transducers. Manufacturing force transducers is significantly more expensive than using commercially available products (the cost to produce some transducers is given as about £4,000), but in applications where such special transducers are required there is no alternative since commercial transducers are inadequate for such investigations. For example, certain research conducted at the Centre requires the measurement of not only normal (perpendicular) force but shear (parallel) force and bending moment as well. No product in the commercial marketplace meets this requirement. However, Bransby (1973) describes the theory, design, manufacture and use of such sensors; at this writing, such devices are routinely fabricated in the workshops of Cambridge University.

30. An example of such a transducer is shown in the photograph of Figure 1 that depicts a central shaft strain gauged along its length and a Stroud force/shear/bending moment stress cell (as described by Bransby 1973) mounted at the bottom. The framework and center shaft of the structure represents/models the leg of an offshore drilling platform which transmits bearing load to the sea floor. A conical foot screws onto the threaded shaft extending from the load cell, enclosing the strain-gauged elements of the cell in a pressure tight compartment. Electronics technicians at Cambridge suggest that silicone sealant containing acetic acid should not be used to seal this compartment since some of the acid vapors will diffuse into the sealed

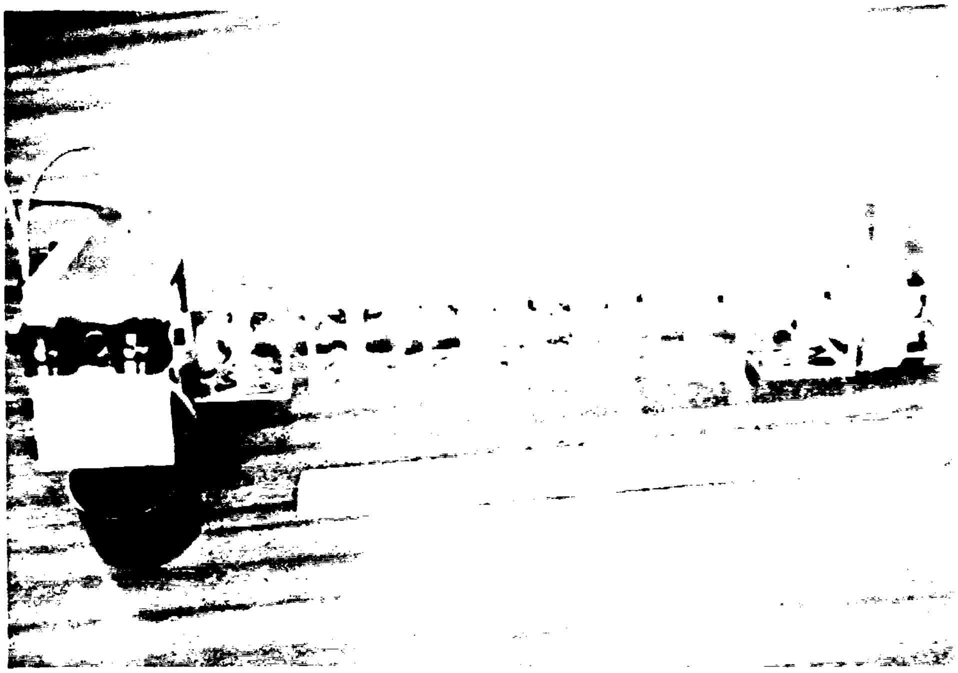


Figure 1. Stroud load cell on model drilling platform leg

compartment where the acid will remain virtually forever. With time, this acid will destroy the strain gauges. To avoid acid damage, epoxies or acid-free silicone sealants should be used to seal such chambers. Additionally, it is advised that strain gauges (even if they are potted) never be touched with fingers, since oils and acids will be deposited on the gauges and will eventually cause damage.

Deformation Transducers

31. Commercially available linear variable differential transformers (LVDT's) are used for deformation measurement on centrifuge models. The point where the cables/leads leave the barrel represents the weakness in these devices. Mechanical handling often causes broken leads at this critical point. Therefore, special care should be taken to protect the leads at the point of separation from the barrel during handling. An additional cause for concern when using an LVDT to instrument a small centrifuge model is that the weight of the core may be significant in the high g-field of the centrifuge. If the material under test is soft, sufficient bearing area should be provided beneath the core to prevent bearing capacity failure and consequent punching into the soil. It should be noted that inadequate footing area for an LVDT

core may generate data that cause misinterpretation of model response. For example, LVDT data may be interpreted as general model deformation when actually the data are associated only with deformation due to the weight of the core exerting high stress on its bearing foot.

32. Linear potentiometers may also be used for deformation measurement in centrifuge models and offer certain advantages. However, when these devices are used, all the precautions necessary for LVDT use and more must be observed.

33. Generally, LVDT's offer ruggedness and relative insensitivity to high acceleration applied by a centrifuge. However, LVDT's have the disadvantage of comparatively large size for (relatively small) associated deformation spans, and in a centrifuge model package, space is at a premium. Conversely, linear potentiometers offer small size with relatively large deformation ranges but are less sturdy (than LVDT'S); flat track potentiometers must be mounted/oriented and supported properly in a centrifuge g-field to achieve best results. Cylindrical wire-wound versions must be used with caution because the g-field of the centrifuge could distort potentiometer windings and change the calibration. An additional disadvantage of potentiometers is that substantial friction may be associated with the movement of the stem.

Accelerometers

34. Accelerometers placed on or within a centrifuge model should be miniature because large (foreign) masses are very undesirable in a vicinity where vibration measurement is being performed. Vibration characteristics in a body of interest may be severely affected by the presence of a large, massive transducer. Additionally, if the volume of an accelerometer is large, stress fields could be disrupted and behavior characteristics changed (see paragraph 28). Researchers at Cambridge University have used accelerometers with external signal conditioning, but they suggest that considerable advantage (in terms of reduced noise and certain types of interference) could be gained using accelerometers with built-in microelectronic signal conditioning; however, these instruments have been available only a short time at this writing. Miniature accelerometers used by the Cambridge team have been piezoelectric quartz devices with about 5 grams mass, typical dimensions 0.56 X 0.51 X 0.37 in., and a maximum permissible continuous sine wave acceleration of

2000-g. Subminiature transducers with 1.5 grams mass, typical dimensions 0.42 X 0.20 X 0.25 in., and a maximum permissible sine wave acceleration of 5000-g have also been used. Accelerometers under consideration to replace the current devices are manufactured by PCB Piezotronics of the United States. The PCB device of particular interest is cylindrical in shape, 0.27 in. in diameter, 0.48 in. high, 2 grams mass and has a manufacturer stated sensitivity of 10 mV/g.

Data Acquisition System

35. Electrical power delivered to various appliances aboard the centrifuge arm is carried onto the arm via mechanical slip rings (in which electrical contact is maintained by holding a spring loaded wiper in continuous touch with a rotating ring of conductive material). Appliances on board the arm requiring power include motors, solenoids, relays, cameras, power supplies, etc. Three-phase alternating current (AC) power (415 V), one-phase AC power (240 V), and 3 to 18 volts direct current (VDC) are taken onto the centrifuge arm to be used as needed for onboard appliances. Power for the various appliances is turned on when needed through solid state relays activated by the DC voltage taken aboard the arm. Direct current excitation voltage for the sensors is produced by DC power supplies aboard the arm (located about 2 ft from the axis of rotation). It is advantageous to use motors driven by three-phase AC power on the centrifuge arm because torque and power produced by three-phase motors are much greater than could be produced by a comparably sized motor driven by one-phase power, and space and weight savings are important considerations. Solid state relays are used on the arm since it is likely that mechanical relays would not operate properly in the acceleration field. The approach used by Cambridge to supply power to the arm is considered advantageous because it allows virtually complete flexibility for obtaining different instrumentation configurations, which might be required for model experiments.

36. Signals/data from sensors are amplified on the arm, then sent (in analog form) through the slip ring assembly to the data recording system. Because of contact motion associated with the slip ring transfer of data, (electrical) noise contamination of data is a potential problem; however, the Cambridge geotechnical team is satisfied that data are not significantly

degraded by slip ring generated noise. Additionally, in power transmission, radiation is associated with the oscillating fields of AC electricity. This radiation may be picked up in leads used to carry electronic signals/data from sensors to the acquisition system and appears as noise at the frequency of the AC (which in Great Britain is 50 Hz).

37. The fact that the strength of radiated pulses decays very quickly with distance is exploited by the Cambridge team to avoid/minimize radiated noise. Power and signal cables are separated by the maximum possible distance at all locations. For example, in the entrance to the beam centrifuge chamber, power cables are run along one wall and signal cables along the other for a distance of separation of about 8 ft. Power and signal enter and leave the centrifuge arm (respectively) through two separate chambers of slip rings (about 7-in. vertical separation), and the signal leads are shielded and twisted pairs to accentuate noise immunity. On the centrifuge, power and signal cables are run on opposite sides of the arm before connection to the package; the distance of separation on the arm is about 4 ft. Obviously then, the lesson learned by the Cambridge team and the technique practiced as a result is to separate power and signal by the maximum possible distance. The use of the techniques described generally revealed no significant evidence of 50-Hz noise in acquired data.

38. Signals from transducers on the model package are brought to a junction box that has been specially designed at Cambridge for use on the centrifuge arm. The junction box contains individual solid state amplifiers; therefore, signal amplification can be performed on the arm very close to the sensors. Amplification factors of 1, 10, and 100 are available through the junction box amplifiers. Additionally, filter circuits as well as circuitry to allow offset adjustment are available through the electronics within the junction box. Externally supplied excitation voltage is directed through junction boxes to various sensors on the package; -5 VDC, 0 V, +5 VDC, and a variable 2 - 11 VDC may be supplied in any combination by setting a network of switches inside the box (the level of variable voltage, that is, 2 - 11 VDC, is adjusted with a trim pot at the arm center). Each individual sensor channel is supplied with a fuse so that if one sensor fails or short circuits, the entire power supply is not overloaded to the extent that general electronic failure results. Each box can accommodate up to 24 sensors/channels which connect using miniature MS31 bayonet locking connectors made to the

MIL-C-26482 specification; (female) bayonet connectors on the box are gasket sealed and leak tight, as is the box itself. Before each experiment, sensors are connected to the junction box, and the junction box/sensor system interfaced with the data acquisition system. Sensors are calibrated through the electronic configuration which will be used during the test.

39. The overall data acquisition system is able to accommodate 57 channels without modification. Data are acquired digitally and manipulated using "LABTECH NOTEBOOK," a commercially available digital data acquisition software package. This package is satisfactory for frequency response in most static tests desired to be performed; it is compatible with the number of channels available in the unmodified data acquisition system at the Cambridge Centre and contains facilities for multiplexing. Along with LABTECH NOTEBOOK, magnetic tape recorders are used as a secondary data logging system. Frequencies up to 10,000 Hz present no problems for the magnetic tape recording systems used, and this medium serves as an excellent analog backup.

PART VI: AUXILIARY COMPONENTS USED IN CENTRIFUGE MODELING PACKAGES

General

40. Sound design procedure in devising physical and mechanical components to be used in the g-field of the centrifuge will require consideration of body forces, which may often be neglected in 1-g. Stresses due to self-weight in the elevated gravity of the centrifuge must be taken into consideration since weight is n times its normal value, where n is the scaling ratio. Additionally, pressures due to (seemingly) small heads of liquid on the centrifuge model package may not be routinely neglected as they are in 1-g. Such pressures may become significant and must be checked and properly provided for if they are determined to be excessive or if they will adversely affect the experiment. Guidance is given by Schofield (1980, Appendix 1) in Appendix A regarding acceptable stress level in some materials, which may be included in model packages, as well as material handling and operational procedure.

41. Attention must be paid to the orientation of components designed for 1-g when they are placed in the elevated g-field of the centrifuge. For example, the shafts/rotors of electric motors placed perpendicular to the centrifuge acceleration field may be distorted to the extent that contact and therefore friction between rotor and stator results in seizing/binding failure of the motor. Disassembly and adjustment of motors in anticipation of their use on a centrifuge model package may not achieve desired results and may even be counterproductive. For example, disassembling a motor and reducing the rotor diameter to prevent contact with the stator may significantly reduce torque which can be produced, thus rendering the motor ineffective. If motor shafts are placed parallel to the centrifuge acceleration field, they may require support on thrust bearings to avoid excessive thrust friction and possible seizure. Thin rotary electric motors and linear electric motors may be used to advantage in centrifuge model packages, but as with all components in the high-acceleration field, such devices must be used with careful analysis, observation, good judgement, and common sense.

42. Solenoid valves used in a centrifuge model package should be oriented with the plunger parallel to the g-field; only solenoid valves with the heaviest coils and restoring springs should be procured for use in model

packages. Additionally, it may be a good idea to give such components "dry runs" and to operate them at test acceleration levels to be satisfied that they will function under the expected acceleration.

43. Generally, because of the harshness of the environment in the elevated g-field of the centrifuge, only the heaviest duty and sturdiest components available should be obtained for use. However, the requirement for strength and sturdiness must be tempered with the knowledge that space is at a premium on the model package. Thus, a balance between ruggedness and small size will be required in selection of components and design of a centrifuge model package configuration.

Fittings and Tubing

44. Fittings and tubing are a necessary part of any soils laboratory investigation; however, in centrifuge modeling, special care must be taken to avoid certain difficulties associated with fittings and tubing that might occur at high-acceleration level.

45. It has been the experience at Cambridge that semirigid nylon tubing and compression fittings may be used without difficulty in centrifuge modeling; however, effort should be spent to keep tubing as short and level (perpendicular to the direction of acceleration) on the specimen container as possible. Care should be taken to eliminate loops from tubes, since the height of a loop will scale to become n times its (1-g) high during flight. Water cavitates at about -33 ft (of water) at ordinary temperatures; this scales to become -0.33 ft or 4 in. on a centrifuge model package accelerated to 100-g. Therefore, a loop in a water-filled tube, which is more than 4 in. high on a model package, is a likely situation for cavitation and "vapor lock" at 100-g. If a bubble of free air is inadvertently left in a tube which should be completely water filled and that tube also has a loop, the potential problem of vapor lock is aggravated. Difficulty associated with vapor lock may be minimized by avoiding loops, by completely saturating tubes with water, and by using high quality de-aired water, if possible. However, it should be noted that problems associated with cavitation do not disappear if high quality de-aired water is used, but they are diminished. Obviously, critical loop height decreases to 2 in. (or less) if acceleration level increases to 200-g.

46. Nylon tubing should be supported whenever possible to prevent excessive pull at the fitting to which it is connected due to centrifugal acceleration. Good practice is to connect nylon tubing external to the specimen container using elbows (right-angle plumbing fittings), since connection to straight fittings will result in an unnecessarily long tube, increased stress at the connection, and possibly an undesirable loop. Elbows should be inspected and cleaned frequently since the 90-deg turn inside them is a potential location for accumulation of foreign matter, which may eventually result in blockage.

47. Standpipes fed with constant water flow (see Figure 2) are useful in supplying constant (pressure) head to a centrifuge model. If it is desired to use a standpipe fed by water flow to supply a constant head to a model package, it is acceptable to simply let excess water fly off the centrifuge

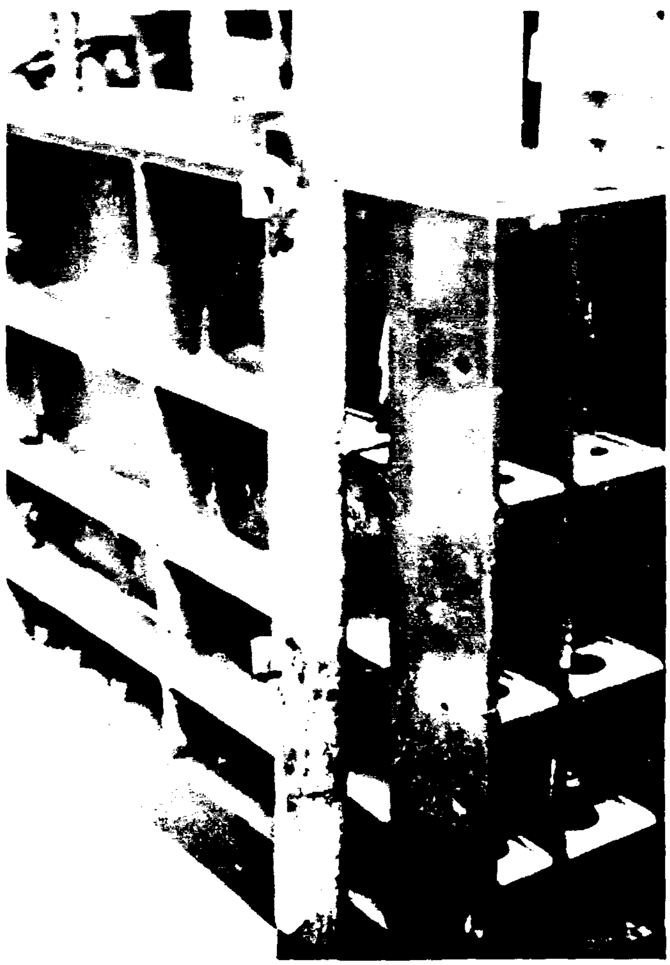


Figure 2. Standpipe on specimen container

arm during flight. Such water evaporates quickly and presents no problems for electronic instrumentation or other equipment on the centrifuge arm.

48. Difficulty can be experienced when attempting to control volumetric flow to a model through a hydraulic slip ring assembly by throttling with a valve external to the centrifuge arm. The reason for difficulty in controlling water flow through a tube running down the arm of a centrifuge (after it has passed through a slip ring) is that if the end of the tube is not closed, centrifugal acceleration will cause the column of water inside that tube to cavitate. It is essentially impossible to precisely control the flow of water which is in a state of impending cavitation. A substantial volume is involved in a hydraulic slip ring; therefore, attempting to control water flow with external valves may result in extraneous (and substantial) volumes of water being inadvertently released to the specimen during flight. Unplanned/uncontrolled releases of water to a centrifuge model are obviously undesirable, and if the amount of water was sufficient, mass balance of the arm could be upset. If there is no alternative but to control flow to models through slip rings, throttling valves should be mounted inboard of the slip rings and near the end of the arm in an attempt to keep the water under positive pressure.

Cameras

49. A charge coupled device (CCD) television camera is mounted onboard the Cambridge centrifuge arm to allow visual monitoring of model packages under acceleration. The camera used is a commercially available monochrome security surveillance model, which was modified at Cambridge for use on the centrifuge arm. The casing of the "off the shelf" camera is relatively large in size but actually houses only two very compact printed circuit (PC) boards. The PC boards and lens assembly are removed from the original housing and remounted in a smaller circular aluminum casing, which is then filled with a silicone rubber-based potting compound manufactured by Dow Corning. The compound is obtained by mixing a two-component system that requires a specific time period to cure determined by the amount of catalyst mixed with the rubber. Power consumption by the camera is low (2 watts), so heat generation and dissipation is not a problem. Reworking the camera in this manner: (a) reduces the size of the camera package; (b) hardens the internal

electronics of the camera for use in the high g-field; and (c) protects the internal electronics from water or high humidity, which may be present in the centrifuge chamber. CCD cameras treated as described above may be mounted inboard of the arm to minimize the acceleration level to which the camera is subjected during a test, or may actually be mounted on the model package at maximum (static) acceleration level. CCD cameras used this way have survived on the beam centrifuge arm for long periods at Cambridge; however, such cameras have not been used aboard packages subjected to dynamic excitation.

PART VII: MATERIALS AND PROCESSING

50. A dry soil powder called Speswhite is often mixed with deionized water to prepare slurry for use by the Cambridge team in model tests requiring clay; it is a commercially available (in the United Kingdom) white kaolin with liquid limit and plastic limits of 69 and 38 percent, respectively, and a specific gravity of 2.61 (Phillips 1986). On the basis of these Atterberg limits, Speswhite falls slightly below the "A" line and is therefore classified MH, inorganic silt of high plasticity, in the Unified Soil Classification System. A grain-size distribution curve of Speswhite (determined by a hydrometer analysis performed at WES) is shown in Figure 3.

51. Speswhite is desirable for use in centrifuge modeling primarily because, although close to the "A" line, it is classified silt and therefore characterized by relatively high permeability at stress levels generally used by the Cambridge centrifuge research team. This silt has the additional advantage that it is commercially available; thus, a dependable supply of uniform material is ensured.

52. In centrifuge modeling, consolidation or reconsolidation of a model on the centrifuge arm is often required. The desirability of a material with high permeability in such a situation is that "in-flight" consolidation time does not become prohibitively long as it might with a more fine-grained and plastic clay. Centrifuge flight time is expensive because the equipment requires large amounts of power and personnel in continuous attendance during flight. Additionally, certain components (such as main bearings) need periodic inspection and routine maintenance after a specific number of hours of use. Therefore, the economic advantage in using a material that consolidates quickly during an experiment is evident. Load response characteristics of Speswhite have been thoroughly investigated in the laboratory; consequently, its constitutive properties are known under a wide variety of conditions. It will be necessary to thoroughly characterize (in terms of constitutive properties) any material(s) selected as a standard for centrifuge modeling. Additionally, it should be mentioned that when a commercially available soil is used, periodic spot checks of its physical properties (such as Atterberg limits, grain-size distribution, and specific gravity) should be made to ensure that these properties do not gradually change with time. If they do, then the

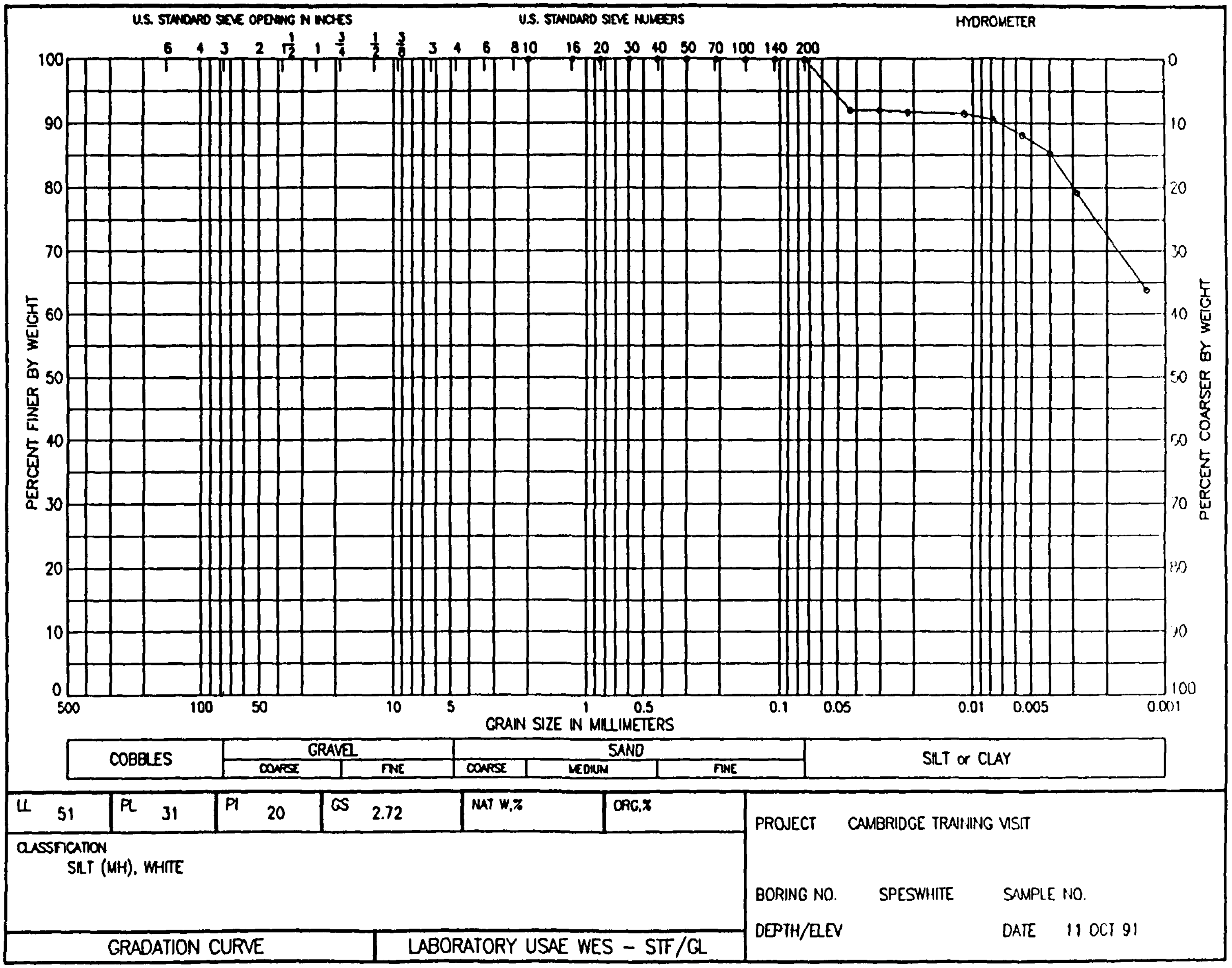


Figure 3. Grain-size distribution of Speswhite kaolin

constitutive properties should be reevaluated to ensure that current comparisons with earlier results are appropriate.

53. Since the behavior of clay is affected by stress history, it is necessary in centrifuge modeling to use a clay with a known and controlled stress history. To achieve such a material, begin with a "virgin" clay, which is then subjected to a desired stress history. A virgin clay is produced by combining a well-disaggregated clay powder with water to result in a mixture that has a water content well above the liquid limit of the clay. Since the resulting slurry is above the liquid limit, there is essentially no particle-to-particle contact within the material; because the particles were disaggregated in a dry state before being mixed with water, all previous stress history was erased/destroyed. A new stress history begins as the clay is consolidated to a desired effective stress.

54. Speswhite clay used in centrifuge model tests at the Cambridge Centrifuge Centre is typically mixed to a water content that is twice the liquid limit in a commercial mixer manufactured by Winkworth Machinery Limited of Berkshire, England. The mixer can accept and effectively handle about 80 liters of slurry at a time. The equipment is configured such that a partial vacuum (24-in. mercury) is applied to the stainless steel chamber during mixing, which is accomplished using counter rotating spiral blades. (It should be mentioned that in addition to Winkworth Machinery Limited of Great Britain, a manufacturer of comparable commercial mixing equipment located in the United States is Charles Ross & Son Company of Happauge, New York; also, there may be other manufacturers of such equipment. Mixing equipment of this commercial quality is used in the drug, food-processing, chemical, and pharmaceutical industries). Mixing time of Speswhite kaolin at Cambridge is approximately 2 hr and results in a very smooth and homogeneous slurry. Application of the vacuum during the process facilitates air removal and ensures a high degree of water saturation in the resulting consolidated clay mass. After mixing, the slurry is immediately put into specimen containers (which might be rectangular or circular in section), consolidation pressure is externally applied in a 1-g environment under the appropriate drainage conditions, and the soil specimen consolidated/rebounded under a series of pressure increments to effect a desired stress history. Because the initial water content and volume as well as the consolidation characteristics of Speswhite clay are

known, a cake of relatively precise thickness can be produced by consolidation.

PART VIII: GRAIN-SIZE EFFECTS AND THE INFLUENCE OF EMBEDDED BODIES

55. A fraction of Leighton-Buzzard sand, which has a maximum particle size of 0.6 mm, is often used in the construction of centrifuge models. At 100-g, this material will scale to become particles as much as 60 mm (2.4 in.) in size. However, the experience of the Cambridge research team (Phillips and Valsangkar 1987) supported by the research of Ovesen (1981) and Yamaguchi et al. (1977) suggest that so long as the ratio of minimum model dimension to average soil particle size is greater than 25 to 36, centrifuge model performance will not be affected. It must be realized that the ratio 25 to 36 is a function of the test and the parameters under investigation. However, in strict light of the grain-size guidance given, problems associated with using large transducers embedded in a centrifuge model become more evident. The use of embedded transducers in centrifuge modeling is necessary for direct acquisition of certain important data (pore water pressure, acceleration) which otherwise could not be obtained. A compromise is therefore made between corrupting model response by embedding sensors and direct observation of important behavior made possible by embedded sensors. Some alteration of model behavior must be tolerated in order to make such measurements. However, minimizing the size and number of embedded sensors and the length of associated buried electrical leads will minimize model disturbance and altered model behavior.

PART IX: INSTALLATION OF PRESSURE TRANSDUCERS IN CLAY MODELS

56. Pore pressure transducers embedded in a centrifuge soil model allow direct observation of pore water pressure response during centrifuge model loading and afford, possibly, the best (indirect) method of investigating effective stress response in soil structures, next to instrumenting and studying full-size prototype structures. It is important that pore pressure transducers be installed in a centrifuge model with a minimum of disturbance to the model. The clay used in centrifuge modeling is typically placed at a water content which is twice the liquid limit, then consolidated one dimensionally to the desired effective stress. Considerable movement occurring as settlement is associated with this consolidation; therefore, pressure transducers must be installed in models after most of the consolidation has occurred because internal soil movement during consolidation would likely damage the thin leads of the (miniature) transducers used in centrifuge modeling. After consolidation to nearly the final effective stress, consolidation pressure is removed for transducer installation. Since installation of pressure transducers must be carried out with consolidation pressure removed, all activities associated with the process should be planned in advance to the extent that all necessary equipment is available so that installation operations proceed quickly, efficiently, and smoothly. Speed of operation may be essential since additional consolidation may be needed after transducer installation, and the time required for consolidation "recovery" after unloading is related to the time during which a soil specimen is unloaded.

57. Pressure transducers are typically installed in soil models through nipples on the sides of specimen containers. Lines of nipples are located at various levels on the sides of model containers. In the case of circular containers, four lines (of nipples) spaced 90 deg apart around the periphery of the container (Figure 4) are found convenient by the Cambridge research team.

58. Specimen container nipples are threaded externally and internally and, for soil placement and consolidation, are closed with plugs placed in the internal thread. Installation of embedded pore pressure transducers begins with removal of the nipple plug; the interior of the nipple is filled with grease before initial placement of soil in the container. Soil may also intrude into the internal thread of the nipple as a result of applied

Figure 4. Nipples on circular specimen container

consolidation pressure. Grease and clay are first removed from the nipple with an auger, then the (internal) thread is cleaned by running a tap through it. An alignment/guide block is then screwed/attached onto the nipple. (See the large cylindrical block installed in the center of the specimen container of Figure 4.) This block has internal threads, which match the external threads on the nipple, and a length of axial bore to guide a thin-walled excavation tube into the model. The excavation tube is constructed of brass, has a wall thickness of about 0.038 in., and is pushed into the specimen through the bore in the guide block to excavate a small tunnel into which a pressure transducer is installed. For convenience and speed of operation, required tunnel depth is marked on the excavation tube before transducer installation begins; during installation, the tube is pushed into the specimen to the mark. The excavation tube has approximately the same (outer) diameter as the pressure transducer. After insertion, an auger rod with an extension is inserted

into the internal bore of the tube to remove clay which enters during insertion (tunnel excavation) as shown in Figure 5. After a tunnel has been excavated and the tube removed, the pore pressure transducer to be installed is

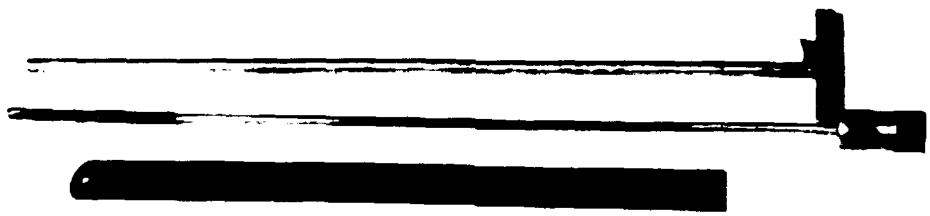


Figure 5. Excavation tube and auger rod

placed on a transducer pusher rod and driven into the excavated tunnel. The pusher rod consists of a brass tube split along a diameter down its entire length with a receptacle at the end for holding a transducer in alignment with axis of the pusher and the excavated shaft (see Figure 6). Transducer leads are deposited in the bottom half of the pusher tube.

59. Pore pressure transducers to be installed in clay specimens are fitted with ceramic porous stones, which are de-aired prior to beginning the installation process. To ensure water saturation, stones are installed on transducers under water just before placement. To be more efficient, ceramic stones used at Cambridge are discarded after each test rather than attempting to recover, clean, and recycle the stones. It should be mentioned here that sintered bronze stones are generally used in sand specimens where the average pore size is much larger (than in ceramic stones), and these stones permit better pressure-time response when silicon oil saturated sand models are tested.

60. After (ceramic) stone placement (under water), the transducer is set in its receptacle on the end of the pusher (also under water) and its

Figure 6. Pusher rod with transducer installed

leads laid in the bottom half of the split tube. The pusher/transducer assembly is quickly taken from the water, brought to the opening in the nipple, and inserted in a smooth thrust. When the enu of the tunnel is sensed (from an increase in force), an additional push of about 5 mm is given to firmly seat the transducer into the soil. At this time, the pusher is pulled back slightly (leaving the transducer in place), and the tunnel filled by extruding clay into the cavity with a pressurized injection syringe. The syringe consists of an O-ring sealed piston chamber (which has been filled with a clay slurry) with a long one-eighth-in. tube attached to its end (Figure 7). The one-eighth-in. tube is next inserted into the excavated tunnel. Then with a threaded shaft to drive the piston, clay slurry is forced through the one-eighth-in. tube and into the tunnel to fill the cavity behind the transducer while slowly removing the pusher rod. With the tunnel completely filled with slurry (Figure 8), a split rubber gland is placed over the leads of the transducer (Figure 9), then installed with the appropriate hardware with just sufficient pressure to seal the electrical leads through the nipple. This procedure is repeated, as necessary, to install additional pore pressure transducers.

61. When all transducers are installed, consolidation load is reapplied. It is suggested by the Cambridge team that transducers can be

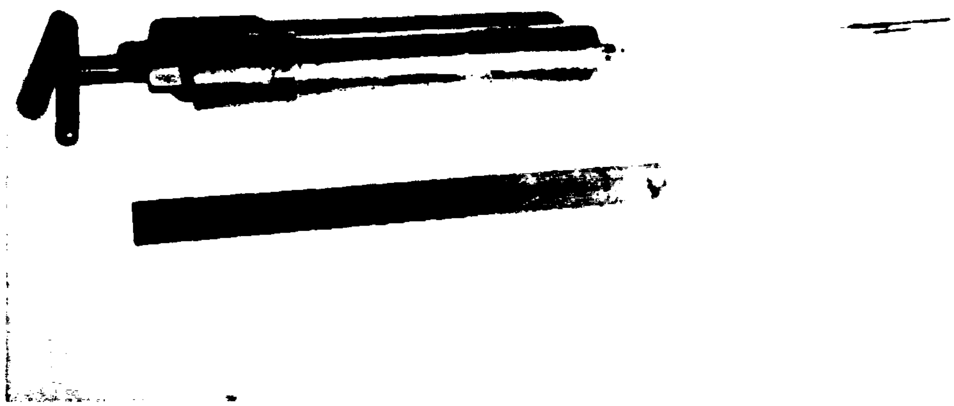


Figure 7. Injection syringe

placed to within about a millimetre of the desired position in the model using the procedure described above.

62. Miniature pressure transducers used in centrifuge research at Cambridge are generally differential pressure transducers (as are most commercially available miniature pressure transducers). It is necessary to vent differential pressure transducers to a reference pressure (usually ambient atmospheric pressure) to obtain a correct and accurate measure of pressure. Miniature pressure transducers are normally vented through the (flexible) conduit used to surround and protect the leads. Since pressure transducers will not indicate correctly if venting is faulty, care should be taken to ensure that the conduit around the leads remains intact and leak tight. If the conduit on a transducer is breached and the device is installed in the interior of a saturated clay model, in addition to the fact that no meaningful data will be acquired by that sensor, the device could be destroyed as the result of water entering the internal electronics.

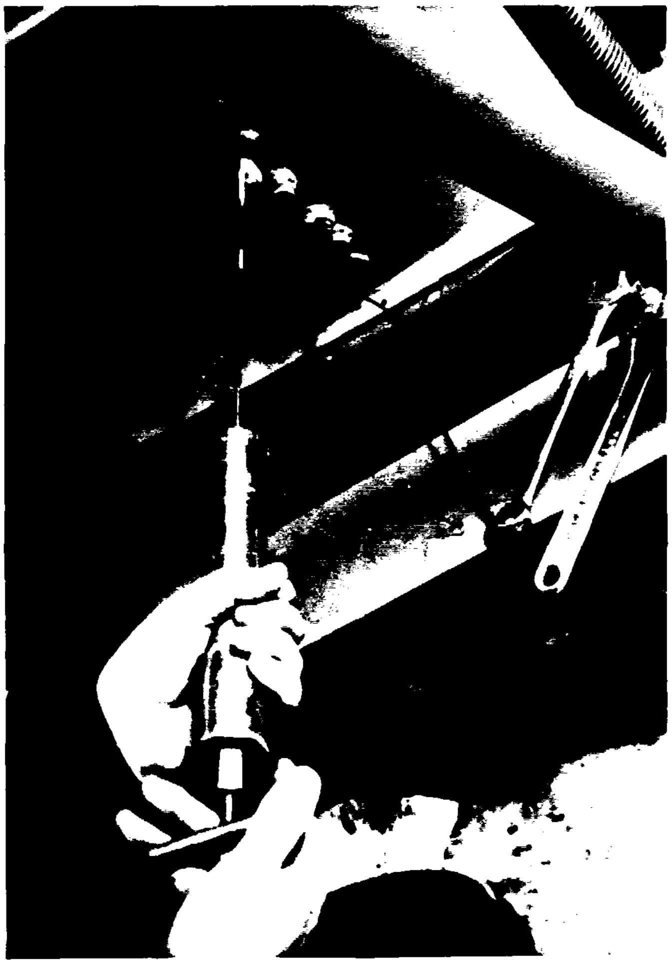


Figure 8. Clay extruding from filled tunnel

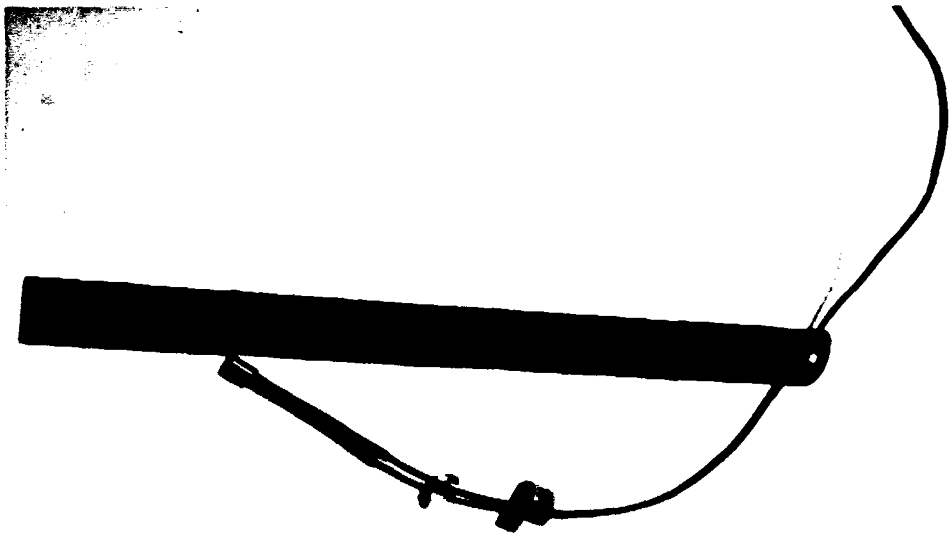


Figure 9. Gland around pressure transducer leads

PART X: EXPERIMENT TO INVESTIGATE LEANING TOWERS ON SOFT FOUNDATIONS

63. As a training exercise, it was determined to investigate the behavior of a tall circular tower to be constructed on a soft foundation using the geotechnical centrifuge. The prototype foundation basically consisted of a surface layer of silt and sand over a layer of slightly overconsolidated clay resting on a sand base. The strength of the prototype clay varied roughly linearly with depth. The decision was made to model the prototype clay with Speswhite and the granular strata with Leighton-Buzzard sand.

64. The planning and design of the experiment determined that the mechanism/phenomenon to be investigated should be represented in terms of effective stress behavior. The attempt would therefore be made to match strength profile between model and prototype, then subject the model to the same stress level as that in the prototype. Overconsolidation ratio (OCR) for prototype soil is about 1.5; its behavior would therefore be the contractive behavior associated with the "wet" side of the critical state line (CSL). However, in order to achieve the same strength profile in Speswhite as in the "aged" prototype clay, it would be necessary to consolidate Speswhite to an OCR of about 3.5 that would produce strongly dilative behavior (which is associated with the "dry" side of the CSL). Behavior on the dry side of the CSL is so different from that of the wet side that it was decided, instead, to scale down stress and strength in the model in order to match the wet side CSL behavior between model and prototype.

65. The soil model foundation would be prepared and subjected to the desired stress history in a large cylindrical (850-mm-ID X 400-mm-high) specimen container. Because clay slurry must be consolidated to high pressure against a sand stratum, it was necessary to establish/ demonstrate that clay slurry does not intrude into the sand stratum during consolidation. The sand used in the odometer experiment and proposed for the centrifuge model is the Leigthton-Buzzard sand. Its particles are typically subrounded in shape. Two size fractions were used in the odometer test to represent the sand strata envisaged for the centrifuge model: (a) a coarse fraction which passes the No. 25 sieve (0.6 mm) and is retained on the No. 52 sieve (0.3 mm), and (b) a fine fraction which passes the No. 100 sieve (0.15 mm) and is retained on the No. 200 sieve (0.09 mm).

66. A layer of the coarse sand was placed in an oedometer, and a small amount of the fine material placed on its surface to act as a filter. Speswhite slurry at a water content twice the liquid limit was then gently placed on top of the sand layer, and the soil/sand composite consolidated to the effective stress expected in the model configuration (140 kPa). Subsequent removal from the odometer and examination confirmed that clay intrusion into the sand layer did not occur.

Preparation of Tower Foundation Model

67. The analysis of the prototype foundation to be represented by the centrifuge model test determined that the required thickness of the clay layer in the model foundation is about 140 mm. The required strength profile could be satisfied by a linear variation in strength in a specimen of Speswhite kaolin consolidated to a mid-height pressure of 140 kPa with a final vertical pressure variation of 70 kPa over the (140-mm) clay thickness.

68. Preparation of the model container consisted of: (a) cleaning the container; (b) placing four circular O-ring seal plugs in the bottom (to facilitate posttest specimen extrusion described later); (c) coating the inside of the container with a thin layer of grease; (d) placing a rubber pad in the bottom of the container; and finally, (e) placing a steel plate on top of the rubber pad (the steel plate will also facilitate posttest model extrusion). The diameter of the steel plate was only slightly less than that of the container.

69. A graded bed of Leighton-Buzzard sand 118 mm thick was then placed in the bottom of the specimen container. The gradation used in the centrifuge model test was slightly different than that used in the preliminary consolidation test: the first layer consisted of 14/25 sand, the second layer 30/52 sand, and the third layer 100/200 sand. The layers were about 62, 53, and 3 mm thick, respectively. After the sand was placed, sufficient Speswhite kaolin at a water content of about 127 percent was placed in the container to consolidate under the anticipated stress to a thickness of approximately 140 mm. (The consolidation characteristics of Speswhite are sufficiently well known to make such an estimate with reasonable accuracy.)

70. It was decided that the clay specimen would be prepared by:

a. Consolidating Speswhite kaolin one dimensionally from a slurry to a final pressure of 150 kPa.

b. Installing/embedding pore water pressure transducers (procedure described above).

c. Reconsolidating the specimen to establish equilibrium under 150 kPa.

d. Applying a downward hydraulic gradient to produce a linear pressure (and therefore strength) gradient of 70 kPa over the height of the specimen.

e. Rebounding to the condition under which the model will be loaded on the centrifuge, which is an effective vertical stress of 140 kPa at mid-height in the clay layer.

Application of Downward Hydraulic Gradient

71. Application of a downward hydraulic gradient allows consolidation which results in a linearly varying pressure gradient over the height of the (clay) specimen. It is accomplished by first releasing the existing load (150 kPa) on the specimen, removing the piston, then placing a (level) layer of sand over the clay surface, and inundating/saturating that sand. This sand simply serves as a drainage layer; it is not a permanent element in the model and is of no particular gradation. A special piston with an inflatable periphery which can be pressurized to achieve a leak-tight seal against the circumference of the container is installed and brought into solid contact with the inundated sand on top of the clay specimen. The original piston load (150 kPa) is reapplied, the peripheral element is inflated to seal the piston, and the sand on top of the clay is placed in communication with a water-filled burette through which (water) pressure may be applied. A layer of sand underneath the clay is present and is a permanent part of the model, so the overall configuration may be represented by the schematic shown in Figure 10. With saturated sand layers at the top and bottom of the clay stratum, piston pressure is increased from 150 to 220 kPa while simultaneously increasing the pressure in the burette from 0 to 70 kPa. Because the increase in pressure over the piston is 70 kPa from the inside and outside (i.e. from above and below the piston), until the valve at the bottom of the specimen container is opened, the specimen "feels" no net change in pressure. However, when the valve at the bottom of the specimen is opened to drainage, the pressure in the sand and at the very bottom surface of the clay layer immediately goes to

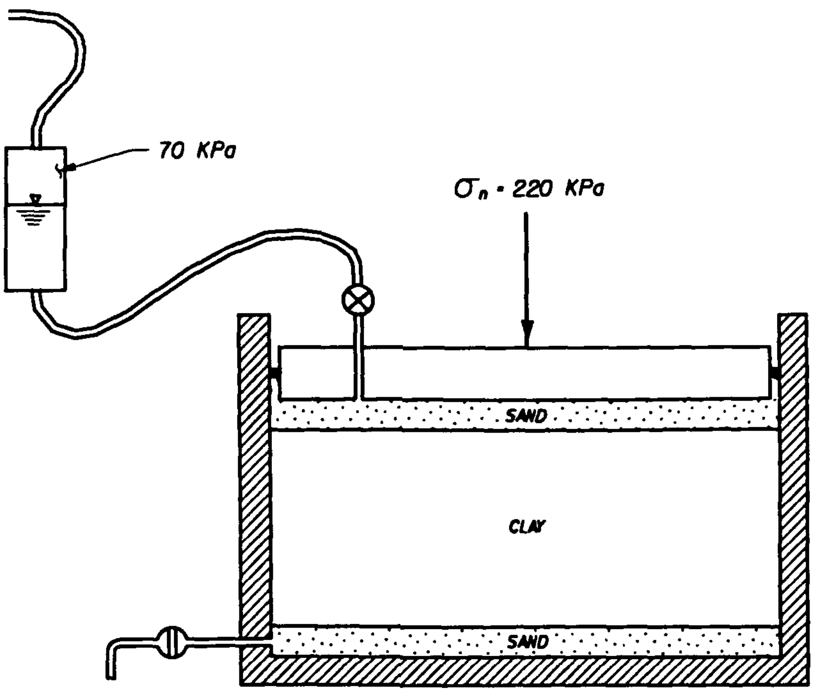


Figure 10. Schematic of leaning tower model foundation with downward hydraulic gradient application

220 kPa, and the vertical pressure distribution in the clay becomes as shown in Figure 11. The hydrostatic pressure (70 kPa) directly underneath the piston will always negate/counteract 70 kPa of piston pressure, so the effective piston force at the top of the clay layer will remain at 150 kPa. However, with time, a steady-state downward hydraulic gradient will be established over the height of the clay layer, and the effective pressure distribution will become that shown in Figure 12.

72. After a steady-state hydraulic gradient is established and the soil allowed to come to equilibrium, 70 kPa is removed from the burette and piston simultaneously, and the specimen allowed to come to equilibrium with access to drainage through the top and bottom (saturated) sand layers. The piston pressure (originally at 150 kPa) is then slowly reduced to achieve the mid-height pressure desired for testing on the centrifuge. In this particular instance, the mid-height pressure is 140 kPa. During all rebounding operations, care was taken to avoid cavitating pore water in the clay specimen; pore water cavitates if vertical stress is suddenly (i.e. very rapidly) reduced by one atmosphere. However, it should be noted that cavitation can occur under

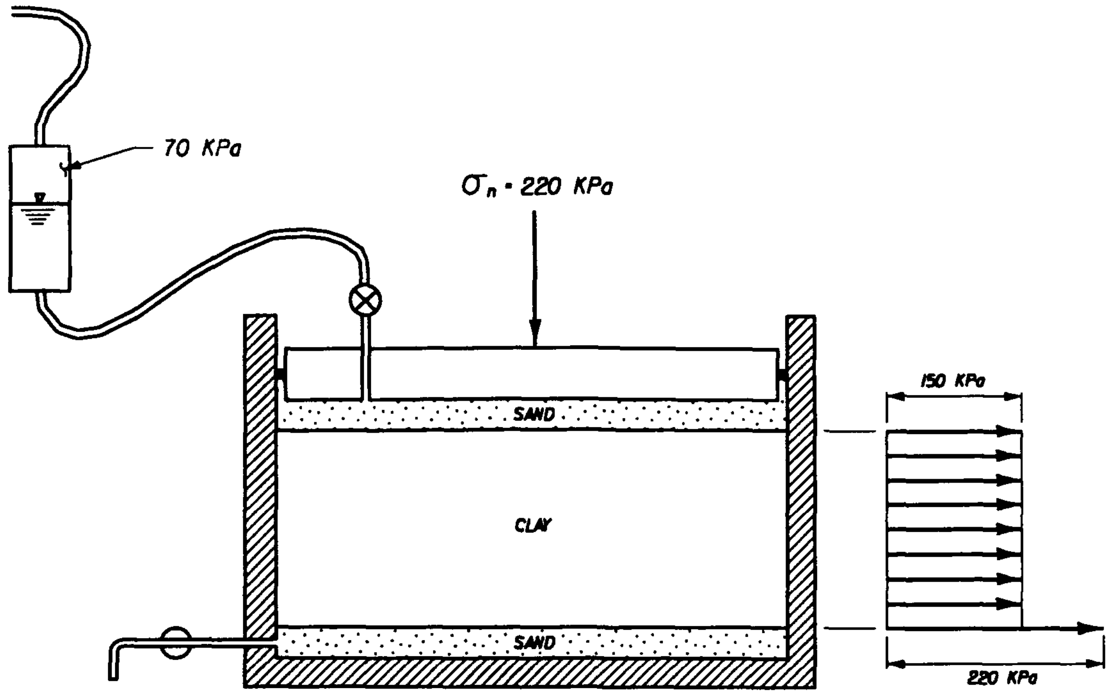


Figure 11. Vertical stress distribution in the clay layer at beginning of downward hydraulic gradient application

smaller stress reduction increments in water with very large quantities of dissolved air/gas. Therefore, sufficient time should be allowed for dissipation of negative pore water pressure during rebounding to avoid cavitation and the consequent loss of saturation.

73. The procedure used (one-dimensional consolidation, downward hydraulic gradient consolidation, then rebound) produces a desired level of overconsolidation in the prepared model foundation. Assumptions associated with the procedure are complete water saturation during all stages, uniform permeability throughout the clay layer, the validity of Darcy's law, negligible material self-weight, and insignificant friction between the piston and specimen container.

Final Specimen Preparation

74. After the model has been consolidated with the prescribed downward hydraulic gradient and rebounded to the desired stress level, piston force is released and the drainage sand layer removed using scoops; the last remaining

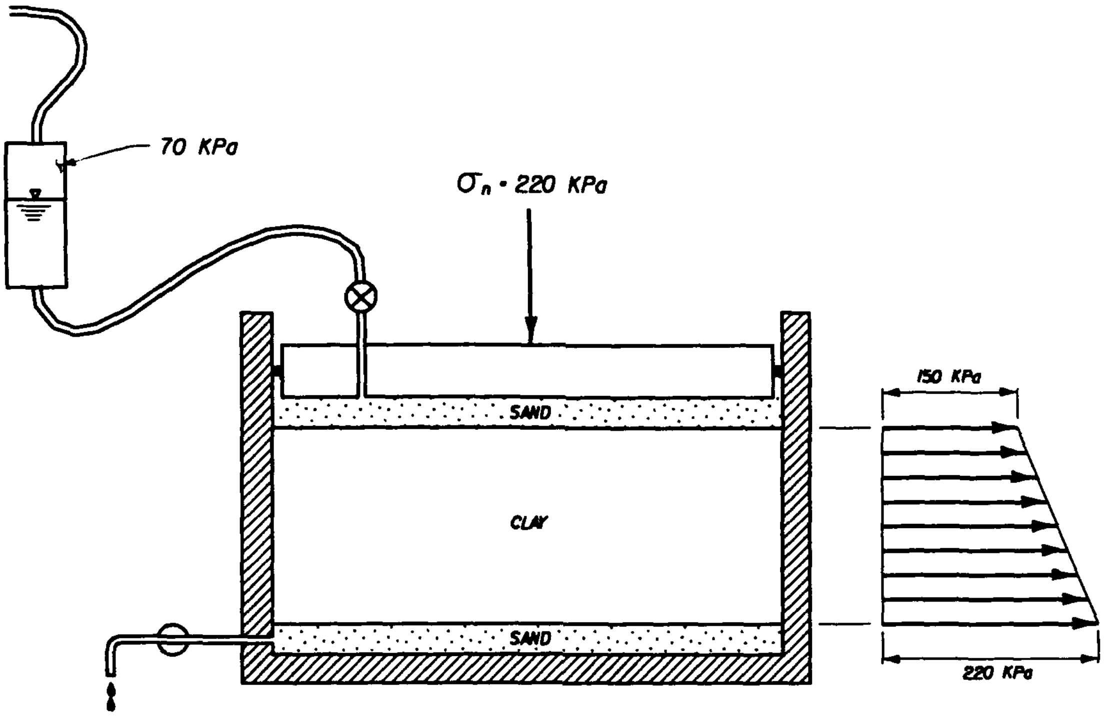


Figure 12. Vertical stress distribution in the clay layer under steady-state downward hydraulic gradient

bits of sand are removed using a wet-dry vacuum cleaner. The clay surface was scraped and levelled to a desired elevation using guide rails and a flat blade/plate clamped to a bar at a distance to provide the required scraping height (see Figure 13). The entire surface was traversed with the blade/plate to yield a smooth, level clay surface. Lead marker beads were then installed in a regular rectangular pattern over the prepared clay surface and photographed so that surface disturbance features (resulting from the applied loading) could be established by comparing the pattern of markers before and after the test. Lead spheres about 0.085 in. in diameter were used along with a template to achieve precise placement of the pattern of spheres. The template was a one-fourth-in.-thick sheet of acrylic that had been drilled with a regular pattern of holes in which the spheres were placed after the template had been orientated correctly on the clay surface. After placement in the receiving cylinders/bores of the template (see Figure 14), the spheres were pushed into the surface a distance of one diameter using a specially fabricated tool. The tool was constructed with a cylindrical tip of such length that after it had been inserted into the bore of the template and had pushed a lead sphere

Figure 13. Technician scraping clay specimen surface to desired height

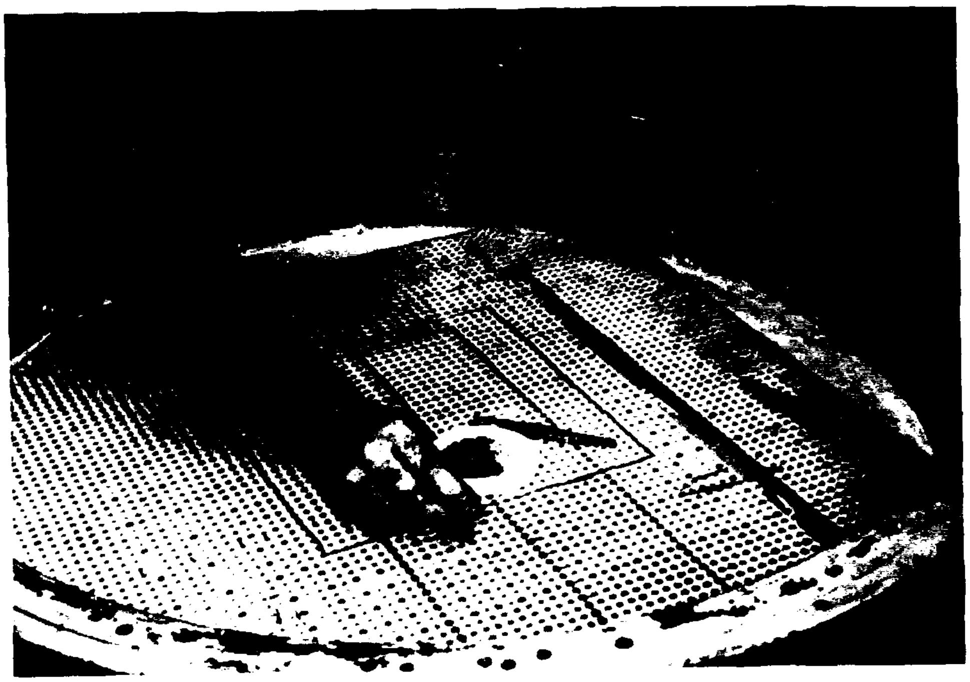


Figure 14. Installation of lead markers on clay specimen

one diameter into the clay surface, a square shoulder at the end of the tip came into contact with the template to prevent further penetration.

75. In addition to the marker spheres, thin spaghetti strands 0.075 in. in diameter were dyed with colorfast ink, allowed to dry, then pushed vertically into the clay in a symmetrical pattern over the plan of the clay surface. Within a few hours, the originally stiff spaghetti strands absorbed water to become soft and compliant so that they could not reinforce the clay and influence stress-strain characteristics of the model. After the experiment, the soft, colored spaghetti shafts would be carefully excavated to investigate internal deformation patterns which occurred as the result of foundation loading.

76. The sand stratum, which would represent the surface, was then placed in a loose state in three layers of about equal thickness. Two marker layers of (Leighton-Buzzard) sand, which had been dyed a dark color with colorfast ink, were placed within the surface stratum to allow identification of posttest deformation patterns. The surfaces on which the marker layers were placed were overbuilt slightly, then leveled using vacuum removal (described above). The dark marker layers were attained by simply sprinkling a thin marker layer of dark sand on top of prepared (levelled) layers. A pressure transducer was installed/embedded in the sand layer by simply placing in the desired location (on a level surface), then covering it with sand. Fittings with tubing were run to the bottom of the sand layer to allow gentle inundation of the top sand layer.

77. The foundation/base of the model tower was to be located beneath the top surface of the soil; therefore, the model tower was placed on a leveled layer and sand filled in around the tower to a predetermined depth to form the top soil surface which was then leveled using vacuum removal. The package was then fitted with deflection and distance measuring transducers and piped for the introduction and planned expulsion of water before and during centrifuge testing. For example, the sand layer on top of the clay was saturated/inundated with water before testing; during the test, a steady flow of water was applied to the standpipe on the model package which was set to maintain water in the model at a level equal to that at the top of the sand layer. In this way, water level, and therefore mass balance, was maintained during the test. Water overflowing the standpipe during the conduct of this or any experiment is simply allowed to fly off the centrifuge and evaporate.

Leaning Tower Representation

78. The tower in the experiment was simulated with a circular acrylic cylinder; foundation loading was applied by filling the cylinder with water during the test. The model package was instrumented with three pore pressure transducers embedded in the clay stratum at two levels and a single pore pressure transducer embedded in the sand stratum, which represents the surface of the model foundation. Two pore pressure transducers in the clay were placed vertically underneath the periphery of the tower, and a third pore pressure transducer embedded in the clay at relatively shallow depth was placed underneath the center of the tower. A fourth pressure transducer was placed inside the tower and used to measure the height of water in the tower (in terms of water pressure at the bottom of the tower). Deformation was measured with 10 LVDT's: three (equally spaced around the tower at 120 deg) mounted on a plate near the bottom of the tower and set to measure tower deflection in the horizontal (with respect to the model) direction; three (also equally spaced and measuring tower deflection in the horizontal direction) mounted on a plate near the top of the tower; three (also equally spaced) measuring vertical deflection of the tower base (and mounted on the bottom plate); and one measuring the surface deflection of the soil foundation near the base of the tower. Tilt of the tower could be determined from the distance between the plates (on which the two levels of LVDT,s were mounted) and the movement indicated by the LVDT's. Springs were installed on the core stems of the (horizontal) LVDT's to keep the probes in solid contact with the tower. No springs were used on the vertical LVDT's since weight of the core assemblies was sufficient to keep those associated probes in contact with the tower base and soil foundation.

79. Since it is desired to simulate a construction sequence, foundation load was increased at a predetermined smooth, continuous rate which was attained by introducing water into the acrylic cylinder at the appropriate mass flow rate. Since the weight of the cylinder had to be supported by the model foundation throughout the experiment, it was not possible to begin construction from zero foundation load. Water flow to the cylinder was controlled with a solenoid valve, and flow rate regulated using a needle valve which was calibrated for discharge. It should be noted that difficulty was experienced in attaining a precise flow rate at the low rate of flow required

for foundation load application because, with time, microscopic particulants suspended in tap water used for the experiment tended to clog up the very small orifice through the metering system. This problem was overcome by sending water for foundation loading through a graded sand filter located on the model package before routing it through the metering system. Provision was also made to remove water/load from the tower (if necessary) by allowing water to exit through a second solenoid valve. A special cradle/frame for fastening solenoid valve(s) to the mounting platforms/plates was designed and fabricated by personnel at the Centre specifically for this experiment since frames supplied with the valves were judged inadequate (in terms of strength and stiffness for the acceleration level of the experiment). The stems of the solenoid valves were aligned with the acceleration field during the test. Since the specimen container on the Cambridge centrifuge is not a true swinging platform, a special wedge was designed and manufactured to correct the small error that occurs between the direction of acceleration and the vertical direction of the model. Since the object of the experiment was to investigate leaning towers, the 1-g error inherent in the Cambridge bucket could not be dismissed as insignificant; so the corrective wedge was used to remove all doubt concerning its relative importance.

Centrifuge Loading of the Leaning Tower Package

80. Instrumentation and the data acquisition system were checked and initialized before application of centrifuge acceleration to the model package. Since a significant element of the model package was clay, acceleration was increased in 20-g increments and held for sufficient time to determine that the tower (and overall test package) was stable under a particular increment. When the final acceleration level was reached, adequate time was allowed for induced pore pressure to dissipate. Pore pressure equilibrium was ensured by observing pore pressure with embedded transducers over a period, then projecting the time for (nearly) complete dissipation using a procedure based on the square-root-of-time technique. It should be mentioned that time for (primary) consolidation was estimated in a preflight analysis of the package, and observed consolidation time (about 4.5 hr) compared favorably with that predicted (about 4 hr) based on previously known consolidation characteristics of Speswhite kaolin. After consolidation, foundation loading was

commenced to simulate prototype loading. It was desired to apply loading in three stages, each consisting of load application followed by a period where load was statically held on the foundation.

81. During the first loading sequence, the tower model began to sink (due to consolidation) and tilt as expected by the Cambridge team. However, when model loading (which simulated anticipated prototype construction) was arrested, tower tilt halted and no further deformation occurred under that load. Pore pressure which developed as the result of loading began dissipating, and the system became stable during the interval between load applications. Under the second loading, the tower again began to tilt (as expected) but tilted so severely that toward the end of this load increment, a fitting attached to the tower contacted the top mounting plate, making any further meaningful load application impossible. For this reason, the experiment was terminated prematurely. However, the experiment yielded very useful information and data and confirmed that behavior/deformation mode observed in the model tower was that expected by the Cambridge team.

Posttest Package Examination

82. After the decision to terminate the test, the centrifuge was brought to a stop, photographs were taken of the package still on the arm, and the model package was quickly removed from the arm for examination and dissection. Instrumentation and appliances were removed from the package carefully and systematically while photographs were being taken of every operation to document the event. Sand strata at the top and bottom of the clay cake were allowed to drain in order to minimize water absorption and hence swell of the model clay. After the top loading assembly had been completely removed, tower tilt was carefully documented photographically. The tower was then removed from the model foundation, and the sand surface profiled by measuring from the top of the specimen container down to the soil surface through regularly spaced holes in a template of the type used to place marker beads during specimen preparation. The geometry and spacing of holes in the template were ideal for this operation.

83. The top sand stratum was then removed in slices to examine and document the internal deformation patterns marked by the (thin) dark sand layers placed during model preparation. Slices were made in the direction

where the maximum tilt of the tower had occurred. The moist sand, held firmly in place by capillary suction, was removed in clean straight slices (guided by lines drawn on the surface) using a wet-dry vacuum cleaner along with a small crevicing tool. A number of slices/sections at regular spacing were made across the model, and each slice was photographed, an example of which is shown in Figure 15. After the plan area of interest in the top sand layer had been sectioned and examined, the remaining sand was removed and the entire clay surface vacuumed clean. The posttest pattern of lead marker spheres were then photographed using the same camera angle and roll of film as had been used to photograph the pretest pattern.

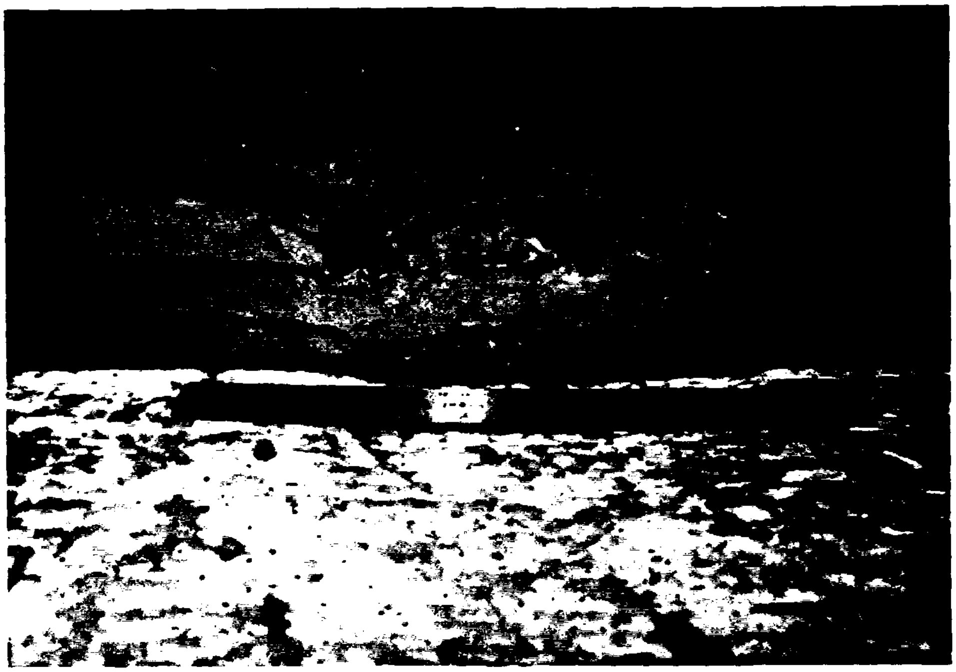


Figure 15. Deformation pattern in horizontal sand layers

84. The location of embedded transducers was established and documented (by measurement) at this point, using care not to disturb the section of clay which later would be sliced and examined. Transducers were removed by cutting the leads (at the connector), removing the associated nipple fittings, and pulling the leads through the nipple from the inside of the container. Transducer damage would likely have resulted if the transducers had been removed from the clay by pulling the leads from outside the specimen container (although this method may seem quicker and easier).

85. When all transducers had been removed, the model was extruded from the container using the four tapered plugs and the steel plate which was put

in the bottom of the container before specimen placement. The container was picked up and set on four vertical extrusion rods; however, the container and rods were positioned such that the head of each rod sat on and fit into a *slight depression* in the four tapered plugs installed in the bottom of the container. Downward force was then applied to the container; the tapered plugs were moved upward from their holes with the result that the rods began to push directly on the steel plate underneath the soil specimen. Additional applied force caused the specimen container to move down and off the soil specimen which then rested on and was completely supported by the steel plate.

86. The (clay) specimen was then sliced to examine the distortion pattern marked by the dyed spaghetti strands placed before the test. A section with the line of markers of interest had been preserved during transducer removal and model extrusion. A wire saw was used to cut into the clay cake adjacent to the section of interest, and soil knives were then used to carefully remove the remaining layer of clay to reveal the vertical sections marked by the dyed spaghetti traces. Photographs were taken to document the pattern.

87. It was hypothesized during planning of the experiment that all phenomena involved in the overall process to cause leaning in the tall tower model could be represented in terms of effective stresses and that the actual leaning would be the result of bearing capacity failure in the foundation. Random variation in the strength of the clay of the model foundation was expected to initiate the process, and identification of the various plastic zones associated with bearing capacity failure was anticipated in the posttest foundation examination. Unfortunately, because the test had to be terminated prematurely, the large deformations which would have occurred during the test were arrested, and the expected plastic zones/wedges (if they existed) could not, as the result, be identified.

PART XI: DYNAMIC TEST ON DRY SAND

88. Dynamic tests are usually performed at 50- or 80-g on the Cambridge beam centrifuge because it has been determined that operation (of the Cambridge beam centrifuge) is smoothest at these g-levels. A series of dynamic tests on dry sand was performed at 80-g to investigate boundary shear transfer. The purpose of the experimental program was to determine if correct dynamic complementary shear stresses develop along the sides of soil specimens in response to dynamic excitation/shear stresses applied through the model container base. Dynamic excitation was applied to soil model packages prepared by packing a space between the sides of the specimen and the container with "duxseal," trade name for a viscoelastic material used commercially to seal air conditioning duct work and used in centrifuge modeling for its vibration damping characteristics. Duxseal is sometimes used to absorb P-waves at the boundaries of dynamically loaded centrifuge model packages and thus minimize their reflection into the soil specimen by rigid specimen container boundaries. The model container in which the experiments were conducted is 48 cm wide X 22 cm deep X 90 cm long. The prepared sand specimens were 48 cm wide, 15 cm deep, and 66 cm long, leaving 12 cm of duxseal between each end of the specimen and the container. Shear stress at each end of the sand specimen was measured by placing a transducer consisting of thin aluminum sheet metal (22 gauge), which has been strain gauged, at the interface between sand and duxseal. It is necessary that the surface of the aluminum sheet be rough for efficient transfer of dynamic shear stress. The aluminum sheet metal transducer in each test was roughened on the side facing the sand by applying a thin coat of epoxy adhesive, then sprinkling it with sand; a surface very uniform in texture and roughness resulted when the epoxy cured. This technique is very effective for roughening metal surfaces to facilitate the transfer of shear stress between metal and sand and is also used to roughen the bottom of specimen containers and the face of (Stroud) stress cells.

89. Instrumentation for the experiments consisted of accelerometers and force/shear/bending moment Stroud load cells (Bransby 1973) as well as the strain-gauged sheet aluminum transducers described above.

90. Soil used for the experiments is the 52/100 fraction of Leighton-Buzzard sand, which is intended to be placed at a relative density of 45 percent. Planning and design of the experimental program by research workers and

engineers began weeks earlier; however, execution of the program began with calibration of the transducers and preparation of the specimen container. Stroud load cells were calibrated with deadweights in the force, shear, and bending moment modes. Axial force was applied with a known eccentricity about the centroid of the cell so that force and bending moment calibration could be accomplished simultaneously. Calibration in shear was achieved by applying known forces in a direction parallel to the load face of the cell with a cable and pulley system. Stroud cells are actually used to determine normal and shear stress in the model by averaging the (shear and normal) force measured by the cell over its face area, which is about 11 sq cm. Stress capacity of the cells used for the experiment in normal and shear stress is about 700 kPa.

91. Accelerometers were calibrated by attaching them to an automatic calibration device that applies precise sine wave acceleration with a maximum amplitude of 1-g at a frequency of 100 Hz.

92. Dynamic loading was applied to the package using the "bumpy road" mechanism (Kutter 1982) in which sinusoidal displacement is applied to the centrifuge model package to produce sinusoidal acceleration. Basically, a sine wave is molded along the wall of the centrifuge chamber, and a cam follower is lowered onto the sinusoidal track at a specified time during the experiment when the centrifuge has achieved the desired acceleration level. Under the bottom of the dynamic specimen container is a gear rack. At some point during the period that the centrifuge arm is being increased to the angular speed necessary to deliver the desired acceleration level, the container swings up and the rack on the bottom of the container engages and locks into the corresponding rack on the centrifuge arm. The cam follower, acting through a gear box, transfers sinusoidal motion/displacement to the rack on the centrifuge arm and thus applies sinusoidal motion and acceleration to the model package in the direction of centrifuge arm rotation.

Container And Specimen Preparation

93. Specimen container preparation consisted, in addition to cleaning, of fastening three Stroud stress cells to the bottom of the specimen container along its long axis at equidistant points. A protective metal channel was placed over the stress cells and fastened to the bottom of the container. The channel was designed to contain three square holes to match the size and

spacing of the stress cells. The height of the channel was designed to exactly match that of the stress cells with a small clearance between the outer edge of the cells and the square holes. After placement of the channel, the clearance spaces between channel and stress cells were painted over with silicone sealant, a material that is relatively weak in shear but prevents the entry of sand grains into the clearance space. Therefore, sand grains did not intrude or wedge into the clearance space, and the cells were free to respond to applied shear stress, normal stress, and bending moment. With stress cells and protective channel in place in the bottom of the container, dry Leighton-Buzzard sand specimens were placed.

94. Sand from a large overhead hopper was directed into the container through a tube which was handheld and moved about, as necessary by the researcher placing the specimen. Density in the specimen was regulated by manipulating the height of fall of sand from the mouth of the tube, and the flow rate by adjusting a damper on the hopper.

95. Specimens 15 cm thick were placed. Temporary level surfaces for sensor placement as well as a final grade surface were obtained by slightly overbuilding the specimen surface, then vacuuming out excess material with an ordinary wet/dry vacuum cleaner and a specially fabricated tool. The tool consists of a short, slotted metal tube welded perpendicular to a longer tube; a guide bar slides up and down the longer tube and can be clamped at any desired level with a set screw (see Figure 16). Sand is removed from a model surface through the slot in the short tube at a level determined by the distance set between the bottom of the (slotted) suction tube and the guide bar. To use the device, a distance corresponding to the desired soil level in the container is set between the end of the suction tube and the guide bar; the guide bar and tube are then clamped tightly using the set screw. With vacuum applied, the guide bar is then traversed over beams placed on the specimen container, and the level of material removed is measured from a datum (usually the top of the container). If the test surface is determined to be at the required level, then the tool is used to traverse and level the entire specimen surface. If the test surface is not at the correct level, the distance between suction tube and guide bar is adjusted and the distance to the test surface is measured until the desired surface level is obtained. This procedure can usually produce a surface within a millimetre of the desired level.

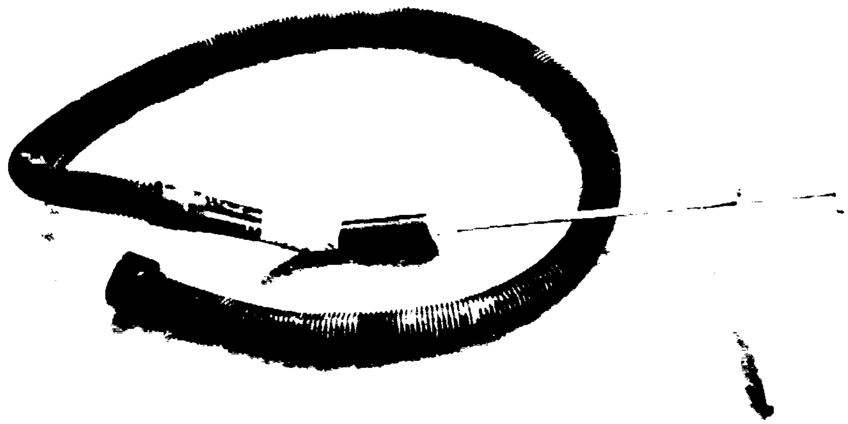


Figure 16. Vacuum leveling tool

96. Accelerometers were embedded in the specimens at predetermined spatial positions. For these experiments, accelerometers were aligned with their axes parallel to the direction of dynamic excitation and the long axis of the container to measure acceleration in that direction. Electrical leads were run along temporary planar surfaces to the nearest edge of the container to minimize buried lead length. Leads were then run up the container edge and tied together with other accelerometer leads using cable ties for eventual connection to a junction box.

97. A top plate assembly was then installed on the specimen container which provided for transducer lead collection and tie down. The top plate assembly also provided locations to ensure symmetric placement of junction boxes and facility for fastening junction boxes in place. When junction boxes were in place and secured, leads from the transducers were connected, secured with cable ties, and all long and dangling ends of the cable ties snipped. Snipping ends off the cable ties served three purposes:

a. It eliminates possible sources of extraneous and confusing movement on the centrifuge model, which would be undesirable and troublesome when reviewing video records of experiments.

b. It serves to give the model a cleaner, neater, and more professional appearance when later reviewed from still photographs (as well as video records).

c. It removes excess weight.

98. Model containers were then moved to the centrifuge arm and installed. The crane used to lift and transport the model and container operated relatively smoothly, without jerking or excessive vibration. However, members of the Cambridge team suggested that a smoother crane would be necessary for moving some packages (in fact, it was suggested that a spring and dashpot mechanism between the crane and container would be required for some packages). A satisfactory crane for specimen transport is essential since stress levels are quite low in small-scale soil models at 1-g. Furthermore, a crane which jerks or vibrates excessively will likely damage or destroy a model that may have required several days of preparation before it reaches the centrifuge.

99. Complete analysis of the data generated by these experiments is incomplete at this writing. However, preliminary analysis suggests that duxseal is an effective energy damper for boundary reflected waves, and correct complementary shear stresses do develop along the sides in response to dynamic shear stresses applied at the lower boundary.

Comments on Testing Simulated Water-Saturated Sand Specimens

100. When performing centrifuge model tests to simulate dynamic loading of water-saturated sand specimens, silicon oil is used by the Cambridge team in place of water to compensate for conflict in time scaling between dynamic loading and diffusion. Prototype sand is often used to construct small-scale models, and as a result soil particles and pore sizes are too large by a factor n. In dynamic loading configurations, time in the model scales as $1/n$ of time in the prototype; however, time in the model scales as $1/n^2$ for diffusive processes such as pore water pressure propagation. Therefore, a conflict of time scaling exists with respect to these two processes. Increasing the viscosity of the pore fluid is a procedure to compensate for this conflict of time scaling. For example, if water is used as the pore fluid, pore pressure will dissipate too rapidly in time by a factor n, and the effect of sustained strength reduction caused by excess pore water pressure is distorted with respect to time. However, if viscosity of the pore fluid is increased by a factor n, then time dissipation of pore water pressure and the subsequent influence on strain and movement will be more correctly modeled. Silicon oil

is used because a desired viscosity can be readily achieved by blending two silicon oils with different viscosities, and the mass density of silicon oil is very close to that of water. (It should be noted that viscosity and density are independent properties and unrelated).

101. At a scaling ratio of $n = 80$, silicon oil with a viscosity of 80 centipoise (cp) is used; desired viscosity is obtained by blending oils with viscosities of 10 cp and 100 cp in the proper proportion. The resulting viscosity is checked with a viscosimeter. Because of its relatively high cost, silicon oil used in modeling is recovered, filtered, and recycled.

102. Because of the high viscosity of the pore oil in modeling and its power to damage a soil model if introduced too rapidly, oil must be introduced/seeped into the soil very slowly and carefully. Additionally, a model must be monitored continuously as it is being seepage saturated with oil.

103. It must be noted that in testing sand models, if a geometric configuration is stable at 1-g and drainage is allowed during centrifuge spin-up, the configuration will be stable at any acceleration level up to the point where stress magnitude in the model becomes so large that failure of individual grains by crushing begins. Thus, something must be <u>done</u> to the model to induce a desired event or effect; increasing the (static) acceleration level alone will not induce an event. Processes to induce desired events are the steepening of a slope during flight, excavation during flight, application of static or dynamic loading during flight, etc.

PART XII: MODELING LIQUEFACTION IN SAND SLOPES

104. Experiments were performed to investigate liquefaction in slopes on the beam centrifuge at Cambridge. The experiments were conducted at 80-g on slopes of sand described as being similar to but slightly finer than the Leighton-Buzzard 52/100 sand fraction. The model was 300 mm wide X 600 mm long and consisted of a dual slope; one 300-mm-long section at the top of the model was at 6 deg and the other section (also 300 mm long) was at 18 deg and ran out to the toe. The model package was instrumented with a number of accelerometers and pressure transducers; the sensors were all embedded in the soil except for one accelerometer mounted on the model box.

105. Because (effective) stresses were very low in the sand slope models (at 1-g), there was very great danger of inadvertent damage to the models during handling and loading onto the centrifuge arm as well as during early stages of centrifuge spin-up. Therefore, it was necessary to handle model packages as carefully as possible during all movement before loading onto the arm and to apply initial centrifuge rotation rapidly to obtain about 10-g. Stress level at this acceleration is considered (by Cambridge centrifuge operators) sufficient to protect the model and ensure its safety against inadvertent damage.

106. After 80-g had been attained, air pressure was used to force oil from a tank onboard the model package into a specially prepared reservoir placed on the upstream side of the model slope. Then oil was allowed to seep into and through the model during flight to establish a steady-state phreatic surface. Viscosity of the oil was 80 cp, and existence of the phreatic surface at 80-g was established by monitoring pore pressure at various points in the specimen during flight. It should be noted that the specific gravity/mass density of the oil used is very close to that of water. Approximately 4 hr were required to establish a steady-state phreatic surface for the geometric configuration, soil, and oil used in these experiments. A sinusoidal earthquake with an amplitude of 26 percent of earth gravity in the scale model (e.g., an amplitude of 20.8-g in actual magnitude on the centrifuge) was then applied using the bumpy road mechanism.

107. Elevated pore pressure was observed from embedded pore pressure transducers as the result of the simulated earthquake. Additionally, both local and general movement were observed and substantiated with instruments

(LVDT's) as well as with visual observation. The initial impression of the research worker was that liquefaction resulted from this dynamic loading; however, extensive analysis of all acquired data is necessary before the occurrence of liquefaction in the model can be definitively established. Analysis of the data is incomplete at this writing.

PART XIII: MODELING CLAY SLOPES

108. Modeling of clay slopes was not observed directly during this training visit. Information given here is summarized from conversations with personnel at the Cambridge Geotechnical Research Centre who have conducted such research.

109. After a clay specimen is consolidated in a rectangular (parallelepiped) container from a slurry, the sides of the container are removed and the model design slope is cut using a taut high-strength steel wire guided by metal templates placed on either side of the soil block. In some two dimensional slope models, a rectangular coordinates system is placed on the lateral surface of the (planar) model to observe the deformation pattern that occurs as the result of loading. High-speed photographs are taken during centrifuge flight to record changes in the grid pattern. Grid points/markers placed are spheres of a polycarbonate material, which has been engineered to have density approximating that of the clay under test. If the density of the marker bodies was significantly greater than the surrounding clay, marker particles would sink during initial centrifuge spin-up and soil reconsolidation; conversely, the particles could be buoyed upward in the model relative to the direction of acceleration if the marker bodies were significantly lower in density than the model clay. Markers constituting the grid are placed with the aid of a template to establish (initially) a perfect rectangular pattern so that strains in the model may be accurately computed based on observed change in the grid. To enable observation/photography of the marker pattern during loading, acrylic plates 3 in. thick are used to laterally confine the model in the specimen container. It is necessary that the plates be thick because they must be stiff to avoid lateral deformation, which could change the stress pattern and therefore the response of the model. Spherical markers were originally used in the grid patterns; however, the image of a sphere could be easily lost if the sphere moved a small distance into the clay. More recently, markers have been designed and used that consist of a cone on one end of a short cylinder and a spherical tip on the opposite end; the diameter of the sphere is large relative to the diameter of the cylinder of the marker. These devices are installed in the specimen such that their axes are normal to the (acrylic) plate with spherical tips of the structure bearing on the plate. Experience with this marker shape has convinced the Cambridge team that better

contact with the acrylic plate is maintained during centrifuge flight than with spherical particles.

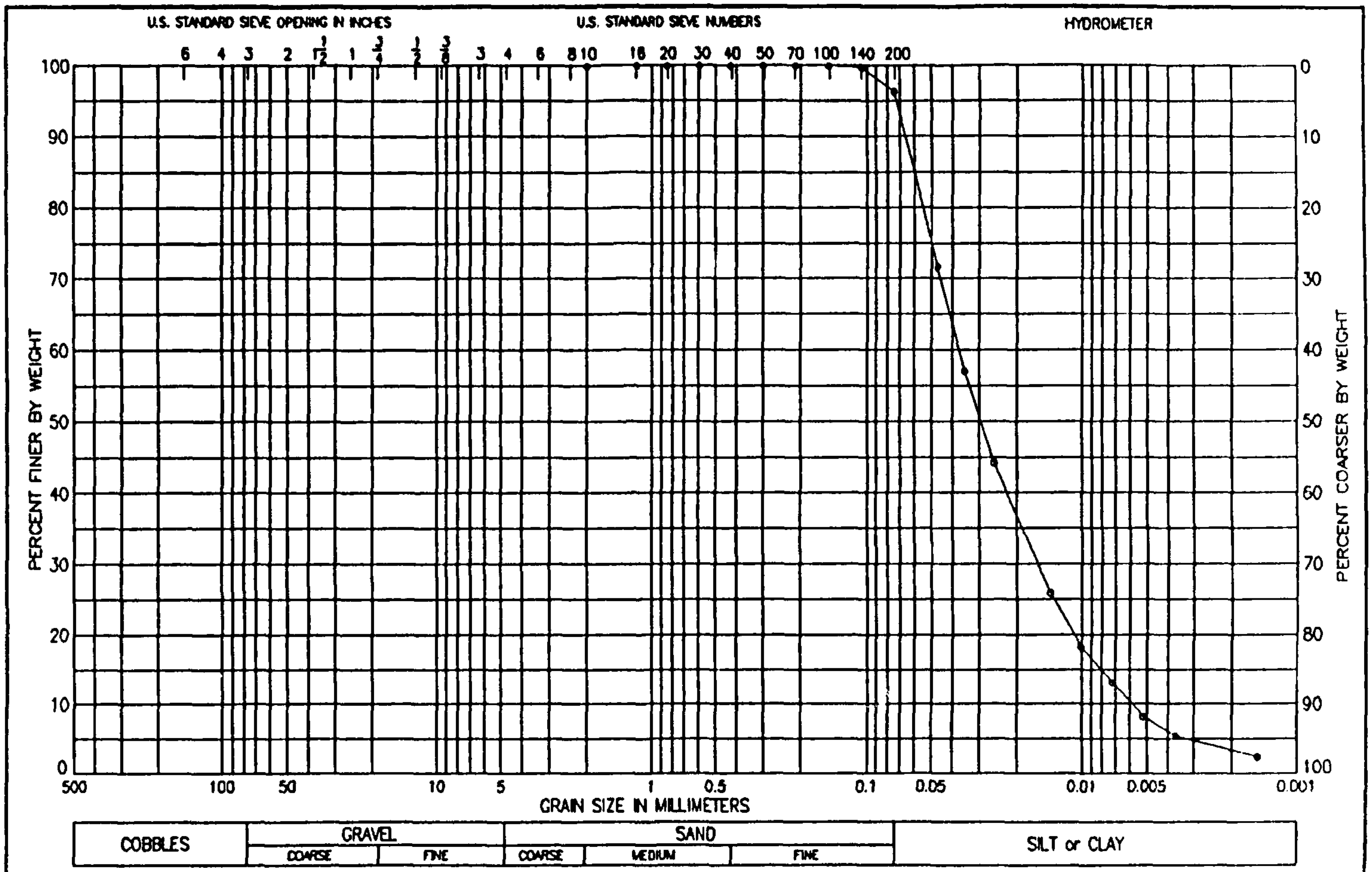
110. Unlike the centrifuge modeling of sand slopes, models of saturated clay slopes must be brought up to rotation speed on the centrifuge slowly. Cohesive forces in clay (which are the predominant stress mechanism acting in clay at low-pressure levels) prevent collapse in models where body forces cause substantial increases in shear stress. Excess pore pressure that develops during spin-up as the acceleration level increases will reduce the effective cohesion of the soil and could cause some models of saturated clay to fail during spin-up. Therefore, it has been determined to initially increase centrifuge rotation speed in several increments, allowing pore water pressure dissipation at each incremental speed and stress level.

111. When desired acceleration level has been reached, the clay is generally allowed to consolidate to equilibrium after which desired loading is applied/induced. Consolidation may be very time-consuming, and it has been mentioned earlier that good centrifuge modeling practice dictates that operating time on the centrifuge be minimized. Therefore, planning an experiment such that minimum time is required for consolidation on the arm is consistent with good practice.

PART XIV: MIGRATION OF HOT POLLUTANTS THROUGH SOIL

112. A centrifuge investigation was performed to study two-dimensional migration of hot pollutants through a soil medium. The model soil used in the investigation is a commercially available ground silica designated 180-grade grit. Specific gravity (determined at WES) 2.66 and a grain-size distribution determined from a hydrometer analysis (performed at WES) is shown in Figure 17. The material is manufactured by Tilcon Limited of Stoke-On-Trent, England, which is a supplier of industrial minerals and products. This particular material is a nonplastic rock flour consisting of silt size particles; it was selected for this experiment because of its high permeability and, therefore, short time required for primary consolidation. The time needed for consolidation on the centrifuge was estimated to be about 45 min. The pollutant in the experiment was modeled with a 0.2 molar solution of sodium chloride salt, and pollution migration was measured in terms of change in salinity with time at various points within the water-saturated soil medium. A high degree of saturation in the soil was ensured since the material was mixed in a Winkworth mixer with vacuum applied; mixing water content was about 30 percent, which is above the liquid limit of the ground silica.

113. The vessel in which the pollutant is contained in the model is a cylinder, 2 in. in diameter and constructed of thin porous steel plate (see Figure 18). The cylinder is of comparable permeability to the soil medium in which it is placed. Heat is generated (to increase the temperature of the pollutant expelled into the soil) by applying about 180-VAC to K-type thermocouple wire, which was wrapped/coiled around the cylinder with sufficient space between the coils to not significantly restrict water flow through the cylinder. K-type thermocouple wire consists of two leads, one of which is chromel and the other of alumel. The heating coil generates about 1,000 watts of heating power and is controlled by an external thermostat circuit to maintain a pollutant discharge temperature of about 50°C. Feedback from a thermocouple on the cylinder serves to control the power circuit. The pollutant cylinder is held in a cradle to secure its location within the specimen container; sensors (which consist of thermocouples, resistivity probes, and pore pressure transducers) are mounted at selected locations in the container around the cylinder. The internal configuration of the model package configuration is shown in Figures 19 and 20.



LL	PL	PI	GS 2.66	NAT W,%	ORG,%

CLASSIFICATION
SILT (ML), WHITE; TRACE OF SAND VISUAL

PROJECT CAMBRIDGE TRAINING VISIT

BORING NO. 180 GRIT SAMPLE NO.

DEPTH/ELEV DATE 11 OCT 91

GRADATION CURVE | LABORATORY USAE WES – STF/GL

Figure 17. Grain-size distribution of 180-grade grit

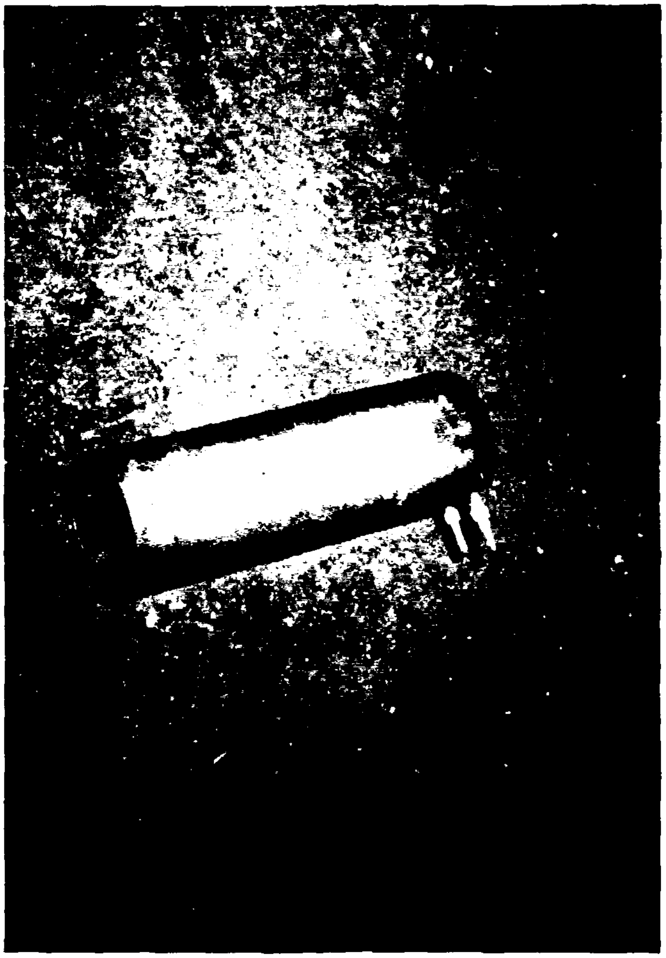


Figure 18. Model pollutant cylinder

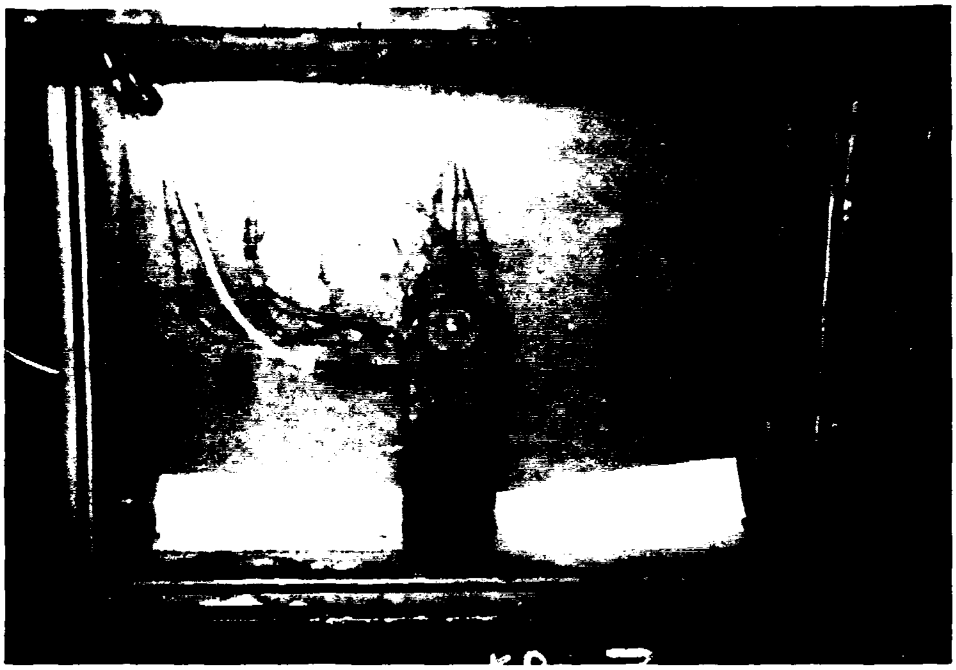


Figure 19. Elevation view of internal model configuration

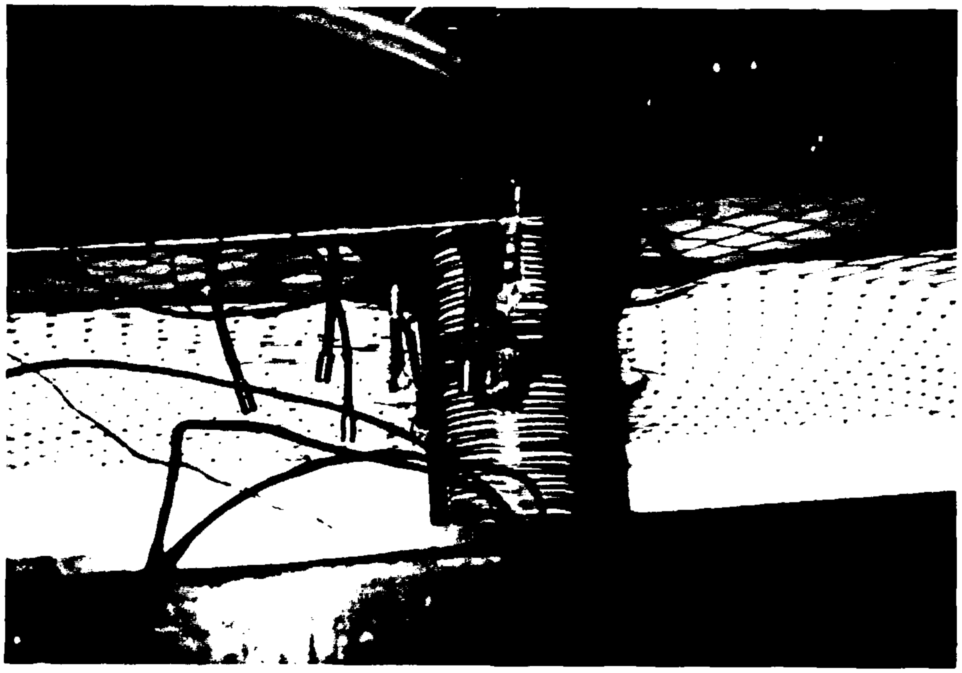


Figure 20. Top view of model configuration showing netting

114. Resistivity probes were calibrated prior to the experiment in saline water-saturated masses of the ground silica, which would be used as the model soil. The calibrations were conducted at approximately the same density as that of the experiment with various concentrations of salt and at various temperatures; the range of salt concentrations and temperatures encompassed by the calibration was the range expected during the experiment. It had been previously determined that the presence of soil around resistivity probes affected the calibration. In fact, calibration coefficients determined in saline saturated ground silica as compared with pure saline solution differed by a factor of about four.

115. Sensors were tied in place on a light "garden net" (thin polyethylene netting) curtain, which was stretched across the specimen container at mid-longitudinal section (see Figure 20). The specimen container was fitted with acrylic side plates because it was determined to X-ray the (soil) specimen after centrifuge flight to accurately establish positions of the transducers during the test. The knowledge of the exact location of sensors is crucial for correct interpretation of data acquired during this experiment.

116. During model preparation, a drain was constructed at the bottom of the specimen container by placing a thickness of coarse sand overlain by a piece of filter paper. Soil-water mixture was then poured/placed into the container over the drain and around the cylinder and sensors and allowed to consolidate under self-weight. Care was taken during placement to avoid entraining air into the soil-water medium.

117. The ends of the pollutant cylinder were sealed with specially constructed caps, one of which was fitted with two tubes to allow the cylinder to be filled with saline solution. During soil placement in the model container, the cylinder was filled with fresh water, which was replaced with saline solution after consolidation on the centrifuge. Replacement of fresh water in the cylinder with saline solution was carried out as rapidly as possible during the experiment by introducing saline solution through one tube connected to the cylinder while allowing fresh water to flow out of the other. (Salt water exchange/replacement in the cylinder required approximately 5 min during the actual test). During model testing, pressure was applied to the saline solution to force it out of the cylinder and into the soil where its movements were tracked with resistivity probes; transfer of heat energy associated with the pollutant to the surrounding soil was observed with

thermocouple probes. Saline water pressure was applied through a constant head standpipe whose level was maintained by a slow, trickling saline solution overflow during the experiment; excess solution spilled off the model package into the centrifuge chamber. A second standpipe onboard the package was continuously fed with fresh water during the experiment to control and ensure a constant water level aboard the package and constant package weight/mass for proper balance of the arm. A rear view of the package showing the standpipes is shown in Figure 21. A front elevation of the package as flown on the centrifuge is shown in Figure 22.

118. Several resistivity probes were embedded in the model to acquire data during this experiment. Because resistivity probes interfere with each other if energized simultaneously, they were switched on and off individually and consecutively for data acquisition during the experiment. For example, a particular probe was energized and allowed to come to equilibrium for 5 sec after which its signal was sampled twice over a 5-sec period, the two samples were averaged, and the result stored. The multiplexing system then switched to the next sensor, which was energized, sampled, and the results stored. These steps continued to be repeated for all probes.

119. This experiment was conducted at 110-g, and some concern was expressed over the fact that heat generated in the model container might seriously weaken the acrylic side plates. Analysis showed this concern to be justified. To alleviate this problem, channel beams were fastened to the specimen container at mid-height of the acrylic plates to provide adequate support for the lateral load expected during flight.

120. Since the soil used in this experiment is a nonplastic silt, and since the experiment involved only flow through a porous medium and not soil deformation, it was determined to purge the model of salt pollutant at the end of an experiment and reuse the soil model for additional experiments. Such a procedure is both practical and sound modeling technique; reuse of the model saves both the time and labor involved in model construction and ensures a (reasonably) identical model for subsequent parametric tests.

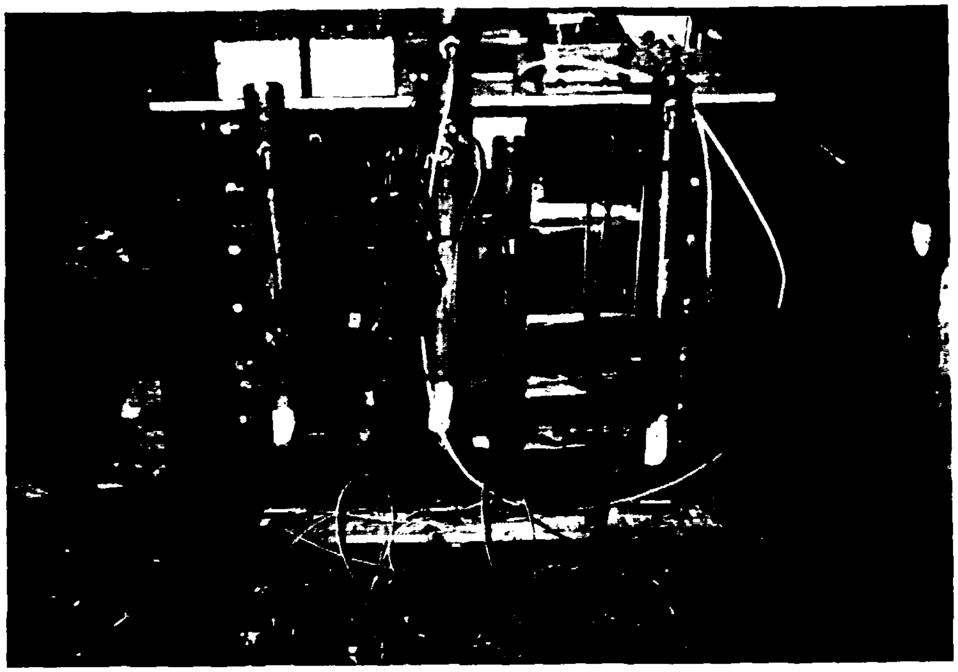


Figure 21. Package read view showing standpipes

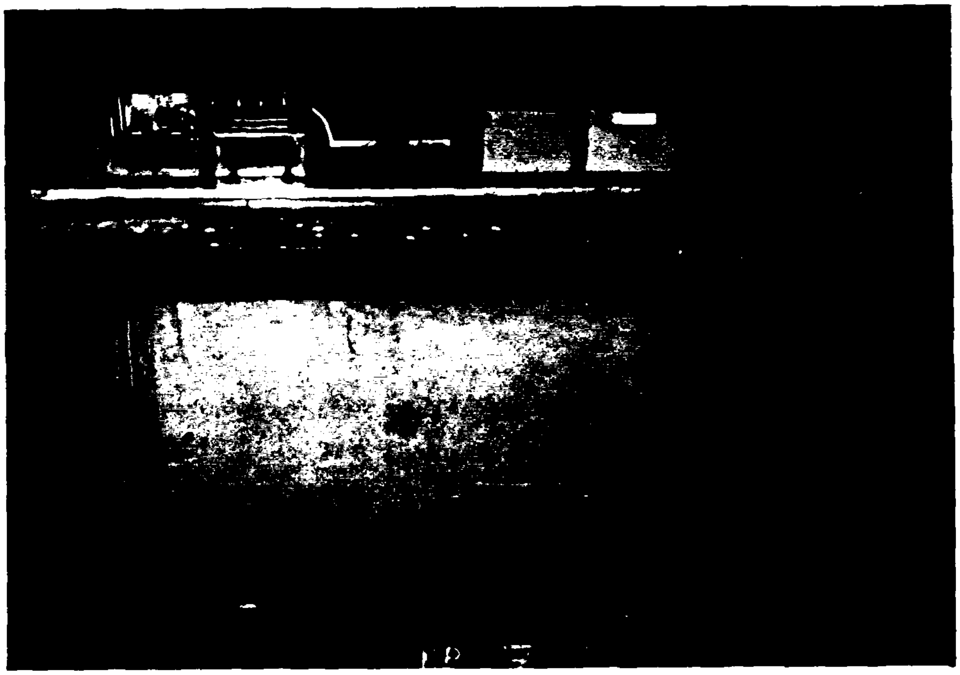


Figure 22. Package front elevation

PART XV: SUMMARY

121. Experienced technicians and personnel at the Cambridge University Geotechnical Centrifuge Centre suggest that geotechnical centrifuge modeling is generally a complex undertaking, and time will be required for new users to become comfortable and competent with the techniques involved. They suggest that there must be an initial period where new users are allowed to become familiar with the use and "feel" of centrifuge equipment, safety measures, and sound procedures for design and execution of experiments. These experienced centrifuge users, however, also warn of the danger of complacency. They state that alertness and focus must be maintained (individually and collectively) at a centrifuge facility along with a serious attitude and a sense of responsibility to the research team involved and to the equipment. The research team concept is stressed at Cambridge with each member of the team having specific areas of responsibilities and accountability. The philosophy/outlook at Cambridge appears to be that although the geotechnical centrifuge is laboratory equipment, it is unlike all other laboratory equipment because of its size, complexity, and the fact that highly organized team effort is required for its safe and effective use.

122. Several experiments observed at the Cambridge facility have been briefly described in this work. What cannot be adequately conveyed in these descriptions is the focus, team spirit, and cooperative attitude on the part of all team members, which make for successful experiments. Almost every test configuration used is new and, to an extent, untried; problems invariably develop during such situations, and each member of the support team does what is required to solve these problems in an efficient, timely, and productive manner. Support equipment, such as small lathes, milling machines, and grinders, allows onsite solution of spontaneous problems, which develop during model and package preparation. Experienced technicians at the Cambridge Centre suggest that the availability of such equipment and personnel able to effectively use it are a necessity at a geotechnical centrifuge facility.

123. Safety of personnel and equipment are a prime concern at the Cambridge Geotechnical Centre. Their record shows that the team approach to safety and the production of quality research is successful. Much can be learned from their organization and technique, the first step of which (they suggest) is the establishment of a committed team.

REFERENCES

Bransby, P. L. 1973. "Cambridge Contact Stress Transducers," CUED/C-SOILS/LN2, Cambridge University, Cambridge, England.

Kutter, B. L. 1982. "Deformation of Centrifuge Models of Clay Embankments Due to 'Bumpy Road' Earthquakes," Proceedings of the Conference on Soil Dynamics and Earthquake Engineering, Vol 1, pp 331-350, A. A. Balkema, Rotterdam.

Ovesen, N. K. 1981. "Centrifuge Tests of the Uplift Capacity of Anchors," Proceedings, Tenth International Conference of Soil Mechanics and Foundation Engineering, Stockholm, Sweden, Vol 1, pp 717-722.

Phillips, R. 1986 (Dec). "Ground Deformation in the Vicinity of a Trench Heading," Ph.D. Dissertation, Cambridge University, Cambridge, England.

Phillips, R., and Valsangkar, A. J. 1987. "An Experimental Investigation of Factors Affecting Penetration Resistance in Granular Soils in Centrifuge Modelling," Cambridge University Engineering Department, Department D, Soils TR 210, Cambridge, England.

Schofield, A. N. 1980. "Cambridge Geotechnical Centrifuge Operations, Twentieth Rankine Lecture," Geotechnique, Vol 30, No. 3, pp 227-268.

Yamaguchi, H., Kimura, T., and Fuji, N. 1987. "On the Scale Effect of Footings in Dense Sand," Proceedings, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Japan, Vol 1, pp 795-798.

APPENDIX A: CODE OF PRACTICE FOR SAFE OPERATION OF THE CAMBRIDGE GEOTECHNICAL BEAM CENTRIFUGE

APPENDIX 1: CODE OF PRACTICE FOR SAFE OPERATION OF THE CAMBRIDGE GEOTECHNICAL BEAM CENTRIFUGE

Introduction

1. The geotechnical beam centrifuge of Cambridge University Engineering Department (CUED) is a research facility on the West Cambridge Site, formerly called CUED 10 m centrifuge, and originally conceived by the late Professor K. H. Roscoe in 1969 as a machine capable of testing models at 250-g. It was constructed with funds which came from the University and the Science Research Council, to the design of Mr. P. W. Turner, by the CUED Engineering Workshops. It now normally operates with swinging platforms which have surfaces at 4.125 m radius so that the sample is at a working radius of 4 m. At the maximum rotational speed of about 186 rpm the acceleration in the model at 4 m radius is about 155-g.

2. Each model must be contained in a strong test package. Of about 20 such packages at present in service about two thirds are circular tubs of 850 mm internal diameter, and 400 mm depth and the rest are rectangular boxes of various dimensions, most with one face including a thick transparent window. Most test packages have undergone a proof test at their own maximum internal pressure, each at the maximum speed obtainable with it, in the presence of an authorized engineer. In subsequent tests in absence of the engineer, the highest acceleration normally authorized is 125-g at 4 m radius. A few packages are designed for use at less than maximum speed: such speed-limited packages are proof tested at 1.25 N gravities before their use at N gravities is authorized. The swinging platform torsion bars are at present adjusted to accommodate a package not exceeding 900 kg mass. Thus in its present operations the Cambridge Geotechnical Beam Centrifuge has 125-g x 0.9 t = 112.5-g tonnes capacity at 4 m radius.

3. The mechanics of consolidation and of yielding soil allow the observation, in centrifuge models at reduced scale and increased acceleration, of events similar to full-scale geotechnical events. This centrifuge has two purposes: fundamental research into mechanisms of failure of construction works in soil or of soil-structure interaction; and training of students, including simulated experience of failure in construction works in soil or of soil-structure construction. Both purposes have been combined in programmes of model tests undertaken by the University under contract to the UK

Department of the Environment or similar agencies, leading to publications and to improvements in Engineering design. Our charge for use of the Centrifuge on contracts with such agencies was set at 500 per day in 1978, which should indicate to all users the value of periods of time they use. The efficient and safe use of the centrifuge for a succession of tests by different people using various packages will be ensured by everyone adopting routine procedures set out below. These procedures can be reduced to the following principles. New users require time to become experienced, and the active group of experienced users have a collective responsibility for efficiency and safety, and for training others. Every test must be discussed and programmed in advance, and any new operation must be calculated and proved safe under the direct supervision of a responsible engineer, with open discussion of all work.

Authorized Users

4. A list of persons currently authorized to use the centrifuge is posted by the Director, and includes names in the following categories.

a. ENGINEERS: all these are employed by the University or by the Department of Engineering as responsible engineers, and have sufficient experience to give engineering approval to the tests of other users, to train other users or operators, to operate the centrifuge, or to use the centrifuge as research workers themselves.

b. CENTRIFUGE OPERATORS: all these are engineers or technicians employed by the University or by the Department of Engineering and have sufficient experience of operation of the centrifuge to advise and assist other authorized users, to verify test documents, mount packages, to start the centrifuge, and to undertake activities as directed by a research worker within an agreed programme.

c. RESEARCH WORKERS: all these are research workers or engineers or visiting engineers with sufficient experience of the operation of the centrifuge to propose programmes of tests and undertake them when approved, and to help train other users.

5. The outcome of each experiment is the concern principally of the research workers, who must discuss with one of the engineers all activities that may be required and describe them in a comprehensive programme set out in advance in the standard programme approval document. The research worker will be present during the mounting of the package and will decide if and when various activities (such as test runs) will actually be undertaken within the programme. When one of the engineers is acting as a research worker then

another engineer must act as engineer for those tests. The research worker is responsible for producing drawings and calculations which must have satisfied the engineer as to the complete safety of the proposed programme before it is approved. The research worker will complete a balance calculation and obtain the engineer's signature on the standard flight authorization document before each flight or sequence of identical flights of models in the approved programme. The research worker continues to carry on-the-spot engineering responsibility for all decisions and for all activities undertaken in the programme. New research workers must expect to spend many days working with experienced users before they can successfully undertake a 'solo-flight'; until then they cannot become authorized users themselves. The facility is constantly changing and the list of persons currently authorized to use the centrifuge also changes, and only includes those with current experience and with a need for authorization; authorization is given by the Director. The normal running of the centrifuge is the principal concern of the centrifuge operator, who will be responsible for ascertaining that all flights have the engineer's approval, that the packages are assembled and secured in the approved and proven safe manner, and that each operation is recorded in the operation book. The operator who mounts a package and sets up an experiment will also start the test flight to ensure that all operations begin normally but during extended periods of operation full operational responsibility can be transferred to another operator. If at any time the centrifuge operator is not satisfied that the facility and the test activities are normal the operator can either ask the engineer to come to check or terminate the programme without the agreement of the research worker.

Programmes and Authorization

6. Research workers who wish to use the centrifuge must give full details as required on the standard programme approval document and place this in the planning rack in the Chief Technician's office well in advance. All proposed programmes will be continually reviewed and in general any one week's programme will be finalized during the previous week. The approval of an engineer and of the Chief Technician indicates that the engineer expects to be able to authorize the tests and that assistance can be provided, but from time to time circumstances in one week may necessitate changes in the timing of the

programmes for the following weeks and research workers must be prepared for this. For proof tests the calculations must have been checked and approval and authorization documents must have been signed the week before a flight: late calculations inevitably result in programme delay. No forward commitment of centrifuge time is made except by fully approved programme approval sheets placed in the planning rack.

7. Each flight of a package needs an engineer's signature on a flight authorization sheet. In a flight of a proof-tested package a sequence of approved activities can be safely undertaken by a research worker and a centrifuge operator in the absence of the engineer. In proof test flights the engineer will be present. In general with previously proof-tested packages before authorizing a flight the engineer will require confirmation from the research worker that the previous proof tests do cover the proposed activities. If it is proposed frequently to undertake a new activity (such as load application) at some particular acceleration of n gravities, this can be checked by calculation and then proved safe by separate tests in which that activity is performed in the presence of the authorizing engineer at 1.25 n gravities before it becomes approved for general use; if n is less than 125 then that activity will be speed-limited to n gravities. The flight authorization sheet will be checked by the centrifuge operator, as will any other points noted by the engineer.

8. The working basis for stressing checks of packages on swinging platforms is as follows. The surfaces of the platforms operate at 4.125 m radius and stressing calculations either relate to acceleration of each mass at its actual radius or to all masses at a nominal 4 m radius. In calculations all containers should be filled with soil to their maximum working level, and all water vessels or air lines should be filled with water either back to the rotor axis and above or to their vent levels if they are vented into the chamber. Calculations allow for means of loading within the package and assume that soil will become fluidized and apply pressures equivalent to a fluid of density 2100 kg/m^3.

9. Packages made of ductile mild steel or dural are designed with full plastic stress redistribution at proof test loading with the following properties.

a. Mild steel has specific gravity 7.83 and may reach 136 MN/m^2.

b. Dural has specific gravity 2.82 and may reach 130 MN/m^2.

These working stresses at proof test conditions each include a safety factor of 2.5.

10. Bolts of Unbrako type are considered ductile if not stressed above 30 MN/m^2 in tightening up and are designed for 275 MN/m^2 in proof test conditions. This working stress includes a safety factor of 3.25. If highly torqued, to ensure a seal or friction joint, bolts must be discarded after 30 uses.

11. Where a perspex window is required it is secured by a metal frame with rounded edges not less than 6 mm radius and is kept free from scoring. In this condition we allow, in calculation for proof tests conditions, that perspex has specific gravity 1.30 and may reach 7 MN/m^2 stress. This working stress includes a safety factor of 2.5 and a stress concentration factor of 2. In other conditions stress concentration factor rises to 3.5 or above. Design of a window as a flat plate of thickness t, depth a, and width b, with triangular pressure distribution, increasing form zero at the top to w at the bottom, and with all edges fixed, follows Roark* (case 70: flat plates) with stress s and deflection y having maximum values

$$s = \beta\omega\alpha^2/t^2$$

$$y = \alpha\omega\alpha sup4/Et^3$$

$$E = 2.8GN/m^2$$

Where other loading or other edge conditions apply the appropriate calculation must be taken from Roark, e.g. for fluid loading see Roark, page 110 for flexure of a beam and neglect the end effects of a flat plate.

---

* Roark R. J. 1965. Formulas for stress and strain, McGraw-Hill Inc., 4th ed.

Table A.1.1

b/a	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
β	0.1308	0.1178	0.2365	0.2777	0.3004	0.3092	0.3100	0.3068
α	0.0016	0.0047	0.0074	0.0097	0.0113	0.0126	0.0133	0.0136

The balance calculation must include a manifest of all masses in the flight package, their centroidal heights x above the swinging platform surface, and the offsets y, z of their centroids from the swing centre where y is measured positive downwards in the pit and z is measured positive to the right in plan view. The total mass and centroidal position of each package before flight must be calculated, and if a shift or change of mass is to occur the largest range must be calculated. The counterweight is calculated on the basis that the steel plates weigh 3.557 kg per mm thickness, and the product of mass times radius of counterweight and package must agree within ± 5 kg m. The centroid must have y > -15 mm to ensure safe swing-up of the platform. The swing-up of each platform is calculated on the basis that swing platforms have mass 127 kg, with centroid 60.9 mm above platform centre, and that the swing axis is at x = 808.4 mm and y = 98.4 mm. Swing-up speeds are calculated within 1/10 rpm.

Operations

12. The flight authorization sheet will name the operator: with operators who do not already have a key, then this will authorize them to obtain the centrifuge key from the Chief Technician. The centrifuge operator will be on hand at the time required in the programme with the building key or keys. In preparing for the test the centrifuge operator will check that signatures on documents relate to the test in hand. Before mounting the package in the presence of the research worker the centrifuge operator will check that masses of tests package and counterweight are similar within 5 kg of those stated in the balance calculation. Before starting the test flight the centrifuge operator will check that the research worker has on hand the set of engineering calculations that relate to the tests, in case these are required by the

engineers. The centrifuge operator is responsible for making entries into the operations book which is kept at the controls.

13. Experience has shown that the presence of visitors during centrifuge flight operations is detrimental to safety and efficiency. The only persons who may attend are those properly concerned with flight operation, such as a collaborator in connection with a research contract or research worker gaining experience; such person should be named on the flight authorization sheet and approval for attendance given at the time of authorization. Other persons wishing to visit the centrifuge do so at their own risk, only on days when there are to be no flight operations, and only at the invitation of, and accompanied at all times by, an authorized user.

14. Before starting the centrifuge the operator will check that all masses in the package and counterweight are properly located and secure, that all people have left the rotor chamber, and that the pit is free from all obstruction or loose objects, and the lids are secure. The pumps and cooling fan are started and the key switch then turned on. The motor starter button is fully depressed, allowing sufficient time for the starter to change to run condition. Availability of all services is ensured and then the Excitation Start button is depressed. The centrifuge operator then goes back to look at the pit and view it from above. On returning to the controls an initial speed increase is pre-set, and wing-up speeds are checked and entered in the operations book. The programme is then started, and activities proceed as directed by the research worker within the agreed programme.

15. In proof test flights the safety doors must be closed. In other test flights the doors may be left open but no one may generally pass beyond them while the centrifuge speed is increasing, or during any activity in which loads on the package are increasing, without the specific written approval of the engineer on the flight authorization document. During a night flight (particularly when consolidating a clay specimen) the research worker may need to sleep but must remain in the building and be able to be woken up by the centrifuge operator without the operator leaving the control room. To terminate the programme, the Motor Stop button is depressed: the pit is then opened for the research worker by the centrifuge operator.

16. In the event of accidental removal of any centrifuge drive system (such as loss of cooling system water pressure through human error) the equipment can be reset by depressing the Excitation Start button. In the event of

a service failure (such as loss of primary circulation pump) the excitation will automatically be removed from the eddy current coupling. If this is noticed the programme must terminate, but it is preferable to let the centrifuge free-wheel to rest and also to turn the key switch to the off position (fully anti-clockwise) and remove the keys rather than to depress the Motor Stop button. Occasionally one of the three services can be restarted in flight by re-setting the overload switch on a appropriate starter box.

17. Table A.1.2 gives the rpm to achieve ng, with g = 9.81 m/s^2.

Table A.1.2

n	rpm	n	rpm	n	rpm
10	47.3	50	105.7	90	141.9
15	57.9	55	110.9	95	145.8
20	66.9	60	115.8	100	149.5
25	74.8	65	120.6	105	153.2
30	81.9	70	125.1	110	156.8
35	88.5	75	129.5	115	160.4
40	94.6	80	133.8	120	163.8
45	100.3	85	137.9	125	167.2